MACHINING OF STEELS WITH CERAMIC TOOLS

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DEDICATED TO MY PARENTS , MY WIFE LIANNE AND MY SONS REZA AND ARIA

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SYNOPSIS

Five different types of ceramic tools of varying chemical compositions, KO60 (oxide based ceramic), KO90 (mixed ceramic), KYON2500 (SiC whisker reinforced) and KYON2000 and KYON3000 (nitride based ceramics) were used to machine three different grades of steel, namely EN8 (plain carbon steel), D2 tool steel (hardened steel) and EN24 (alloy steel) under various cutting conditions. Throughout the experiments various cutting speeds were used (50 - 700 m/min) for each of the cutting tools and work materials under investigation. The feed rate and depth of cut were kept fixed. The objective of these tests was to assess the optimum cutting conditions of each grade of ceramic tools used when machining steels. In all cases, the worn tools were examined to identify wear mechanisms and to determine how the wear was affected by the nature of the different workpiece, tool materials and variables such as cutting speeds. Furthermore, in order to understand the condition at the tool/chip interface cutting forces and surface finish were also measured.

The results showed that the tools failed mainly by flank face wear. The wear mechanism analyses suggested that attrition, diffusion and plastic deformation controlled the tool life. At slower speeds, attrition has been the dominant wear mode, where as at higher speeds, evidence of diffusion and plastic deformation was the dominant wear mechanism.

From study of the microstructure of ceramic tools, it was found that materials having smaller grain sizes gave the best tool life. It was also found that the large glass islands of nitride based ceramics enhanced attrition and diffusion wear resulting in a shorter tool life.

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LIST OF ABBREVIATION

BUE	Built Up Edge
CBN	Cubic Boron Nitride
C.L.A	Center Line Average
Co	Cobalt
CNC	Computer Numerical Control
Fe	Iron
HFC	Hafnium Carbide
HFN	Hafnium nitride
HIP	Hot Isostatic Pressing
HSS	High speed steel
KO60	Pure Oxide ceramic tool
KO90	Mixed Oxide ceramic tool
KYON 2000	Nitride based ceramic tool
KYON 2500	Silicon Carbide Whisker reinforced Alumina ceramic tool
KYON 3000	Nitride based ceramic tool
NC	Numerical Control
R.M.S	Root Mean Square
SEM	Scanning Electron Microscope
Si	Silicon
SiC	Silicon Carbide
SiCw	Silicon Carbide Whisker
Ta	Tantalum
TaC	Tantalum Carbide
Ti	Titanium
TiC	Titanium Carbide
TiN	Titanium Nitride
TRS	Transverse Rupture Strength
V	Vanadium
W	Tungsten
WC	Tungsten Carbide

LIST OF SYMBOLS

A	Area above and below the mean line
Fx	Feed force
Fy	Radial force
Fz	Cutting force
H(theor)	Surface finish value theoretical
h	Cordinate from the center line
L	length of trace
r	Nose radius
S	Feed
T	Tool life
t1	Depth of cut
t2	Chip thickness
V	Cutting speed
α	Rake angle
ψ	Shear plane angle

CHAPTER 1

1.0 INTRODUCTION

The importance of the metal cutting process may be realised by a single observation; that nearly every device in use today has either a machined surface or a hole drilled in it. Metal cutting is a major part of today's industry. The industries in which the machining process is an essential process include the motor car industry, electrical engineering, aircraft manufacturing, ship building, the railways, the production of domestic equipment as well as the machine tool industry itself.

Such an immense machining activity in industry means that millions of people are directly engaged in the field of machining throughout the world. Computer controlled machining operations are now underway; the introduction of which resulted in a considerable reduction in the costs involved, thus causing a further increase in metal cutting in the engineering industry.

The industrial revolution may be regarded as the beginning of modern machining technology. During this time up to the present day, many types of cutting tools have been developed and have been in use. These include high speed steel tools, carbide tools, ceramic tools, diamond tools and cubic boron nitride tools (CBN). All of these materials were developed with the objective of increasing the productivity and to achieve greater precision in metal cutting processes.

The need for the development of cutting tool materials that have mechanical, physical and chemical properties superior to those of carbides at room temperatures is high. Material scientists, metallurgists and cutting tool engineers have worked towards developing materials that can cut at faster rates through higher cutting speeds, feed rates and greater depth of cuts. Cemented carbide tools have high fracture toughness next to high speed steel tools; they are however less stable chemically than ceramic tool materials (7). For instance, this will tend to increase tool wear at high cutting conditions which increases metal removal rate. An ideal tool material would be one which is hard, tough and chemically inert both at room and elevated temperatures. Ceramic seems to be an obvious choice for such a material. Ceramic tools are regarded as having a lot of potential due to their chemical and physical properties and the range of applications they may be used for. Ceramics as tool materials, have proved to be very successful particularly as cutting tools for use in high speed machining. They are chemically inert, retain their properties at high temperatures and are particularly recommended for use at higher cutting speeds.

At present, nickel based alloys and cast iron are being successfully machined with ceramic cutting tools. The machining of steels is not yet recommended with ceramic tools because they are the most recent cutting tools available on the market. Detailed studies of the behaviour of these tool materials has not yet been undertaken (7). However, various workers have found a potential for the use of ceramic tools for machining steel.

The use of ceramics for the machining of steel is very limited due to the problems generated during the machining process. With the ever increasing use of more rigid NC/CNC machines, these tool materials have started to find more use in industry. Therefore, this project was set up in order to investigate the use of various grades of ceramic tools; namely KO60 (oxide based ceramic), KO90 (mixed ceramic), KY2500 (SiC whisker reinforced) and KY2000 and KY3000 (nitride based ceramics) which are all manufactured by Kennametal Inc. for the machining of three widely used steels in the engineering industry, namely EN8 (plain carbon steel), D2 tool steel (hardened steel) and EN24 (alloy steel).

This research has been conducted in two main areas:

1) To determine the optimum cutting conditions of each grade of ceramic tool used, when machining three different of steels.

2) To understand the wear mechanism and failure modes of the cutting tools.

To achieve this, machining tests were carried out to determine tool life at various speeds (50 to 700 m/min in steps of 50 m/min) using the ISO recommended criteria. Some parameters have been chosen in line with the previous work carried out on ceramic tools at the Warwick Manufacturing Group. This was followed by the examination of worn tools in order to observe the failure modes and wear mechanisms. Effects of various cutting parameters on these failure modes and wear mechanism have also been studied. Further investigations were carried out to determine the rate of wear. These include investigations of the conditions at the tool tip through the measurements of cutting forces and the chip and surface finish generated on the work material.

CHAPTER 2

2.0 LITERATURE SURVEY

2.1 HISTORICAL BACKGROUND

The use of cutting tools dates back to the prehistoric ages, when man used stone tools as drills and knives. It is an established historical fact that Egyptian artisans used flint tools for boring the inside of vases as early as twenty-five centuries B.C. It is thought that the first real lathe was developed in the Bronze Age in the Indus Valley for the cutting of wood (1). These lathes were rotated on the principle of retention of elastic energy and hand held tools were used to cut wood. Such simple lathes were widely used throughout the middle ages up to the industrial revolution.

It is important to note that, in fact up to the 18th century, the main material used in engineering structures was wood. The lathe and a few other machine tools existed, mostly constructed in wood and most commonly used for shaping parts. The exceptions in this were the boring of cannon and in the production of metal screws as well as in the production of small instrumental parts. The first major breakthrough in metal cutting was due to the invention of the steam-engine, (2) which with its requirements of large metal cylinders and parts of unparalleled dimensional accuracy led to these developments in metal cutting. The materials from which the steam engine was constructed (eg. grey cast iron, wrought iron, brass and bronze) were, however, not difficult to machine and were easily cut using hardened carbon steel tools. These were reliable tools but in order to avoid rapid failure, the cutting speeds had to be very low leading to poor surface finish. The cutting tools also lacked adequate strength overall which resulted in low productivity due to limited metal removal rates.

Further development of more difficult to cut materials such as steel, which replaced wrought iron for most purposes, consequently led to even further reduction in the cutting speeds achievable with the carbon steel tools. It is interesting to note that some sources indicate the use of steels in the manufacture of earlier tools. For example, the Wootz steels of India were made from sponge iron in a crude forge. After hammering iron and remelting it with wood, a uniform steel was obtained. Steel making is also thought to have been practised by the Chinese as early as 1000 BC.

Later Damascus steel which is a very famous steel was made by welding alternate thin strips of steel and soft iron by twisting and working. The Toledo steels of Spain were made soon afterwards. During the fifth to the eight centuries, the so called Dark Ages, steel was manufactured by heating iron in contact with charcoal. In Europe prior to 1740 steel was made by carburising. In 1820, Karsten established the fact that differences in the forms of iron and steel were due to differences in the Carbon content (3).

It was at this stage that the emphasis was directed to the development of tool materials rather than the development of basic machine tools. The objective was to develop tool materials which could withstand the severe conditions in metal cutting; such as tools which could cut at higher cutting speeds with deeper cuts using higher feed rates, in order to increase productivity and reduce the cost of the machined end product.

Later in 1898, through extensive and detailed studies, F W Taylor discovered that a relationship existed between heat treatment and tool performance for steel alloyed with about 5% Tungsten (W) (4). In this work, he had set out to investigate the effects of tool material and cutting conditions on tool life during roughing operations to try and find empirical laws which would predict the optimum conditions. As well as this, he had also discovered that the temperature at the tools cutting edge controlled the wear rate and overall presented the relationship stated at the beginning of this paragraph (4).

Taylor's investigations led to the invention of High Speed Steel (HSS) tools (1906). With these new high speed steel tools the cutting speeds achievable were increased by a factor of four. Taylor also found that best high speed steel composition should contain about 19% W. High speed steel tools of this composition were observed to be able to withstand temperatures of up to 650 degrees centigrade (4).

By the 1930's, due to further improvements in the manufacturing techniques and heat treatment processes, the cutting speeds achievable by HSS tools had been optimised to a value of about 80m/min when machining mild steels.

The next major development in tools followed shortly after the high speed steels with the introduction of the cemented carbide (WIDIA) from Germany by Schroter (5). This enabled the cutting speeds to increase several fold. The introduction of cemented carbide, most commonly made from fine powders of tungsten carbide and cobalt, proved to be the most important and significant invention to affect cutting tools. In the early days of their usage, there had been complaints about their brittleness, unpredictability and chipping. However, the use of various alloying elements were then found to have improved the toughness of carbides to an extent that they could be used for all sorts of machining operations. By 1933 the cemented carbides could cut mild steel at a speed of 250m/min compared to a maximum of 80m/min previously with HSS tools.

The introduction of ceramic tools, another range of tool materials in 1950s, further extended the range of cutting tool materials. Ceramic tools were developed at the same time as cemented carbides. However, their importance was not fully realised until World War II when there was a reduction in the supply of tungsten required for the manufacture of cemented carbides. This lead to the choice of the ceramic tools as an alternative. Originally ceramic tools were either made from silicon carbide or alumina. The latter was found to be more favourable in its properties especially in the accomplishment of high speeds and it was established that it could cut metals at higher speeds than HSS and cemented carbides. Tools based on alumina have been very successful for the machining of cast iron. Its use in machining of steels is very limited due to its poor thermal shock resistance and low toughness which could lead to premature fractures during machining (7).

The extensive search carried out by material scientists, metallurgists and cutting tool engineers, for stronger ceramic materials of better performance in severe applications has resulted in the development of three alternatives namely; i) cermets, ii) polycrystalline diamonds, and iii) Sialon ceramics.

Cermet is an alumina-titanium carbide base tool material and possesses mechanical properties similar to those of alumina. However, in comparison to alumina ceramics, it has better thermal conductivity at temperatures above 600 degrees centigrade, resulting in better thermal shock resistance (6). The second alternative, the polycrystalline diamonds have shown extremely high potential for use in the machining of various materials but their cost is too high. The third alternative, sialon ceramic is based on silicon nitride and has proved to be highly successful for the machining of super alloys based on nickel and titanium (7).

Further to the development of these tools, other contributions have also been made resulting in improved productivity, cost and surface finish. The optimisation of the tool shapes for example, led to longer tool lives at higher cutting speeds. Many coolants and lubricants are also now available to increase metal removal rates and improve surface finish. Machine tool manufacturers have developed machines capable of making full use of the new tool materials, such as automatic machines, numerically controlled (NC) machines, often with computer control (CNC), and transfer machines to greatly increase productivity per worker.

As industry progresses, it is obvious that the conditions that the materials are subjected to become more severe and there is, hence, a constant need to meet these changing conditions.

2.2 THE METAL CUTTING PROCESS

The cutting of metals is one of the most common and economical methods of producing components in engineering. The process basically involves the removal of a thin layer of work material, known as the chip or swarf, by the action of a wedge shaped tool driven asymmetrically into the workpiece material. The metal removed encroaches upon the rake face of the tool and moves over it in a direction away from that which the body of the metal is moving and so is separated from it. An understanding of the mechanics of the metal cutting process is very important, although it is somewhat complex and its full appreciation requires consideration of some aspects of solid state physics, physical metallurgy, engineering mechanics, thermodynamics, theories of wear and lubrication and inter-relation in metal cutting. Thus, understanding the process refers to conditions involving intense deformation of metal, combined with high localised pressure and steep temperature gradients at the chip, tool interface.

2.3 THEORIES OF METAL CUTTING

The mechanics of chip formation have been studied by many authors and it is now widely accepted that chip formation is a plastic shearing process and that the deformation is extremely localised (9).

Basically, the chip formation process can be best explained by considering the two-dimensional simple case, 'orthogonal cutting' in which a single cutting edge is perpendicular to the relative motion between the tool and workpiece. In practice, actual cutting operations often involve a cutting edge which is inclined at some angle other than 90 degrees to give 'oblique cutting'. However, the nature of the chip formation process is similar in both cases.

The first complete analysis providing a so-called 'shear angle solution' was presented by Ernst and Merchant (8). In their analysis the chip was assumed to act as a rigid body which is held in equilibrium by the action of the forces transmitted across the chip-tool interface and across the shear plane. Figure 1 shows the system of forces in orthogonal cutting with a continuous chip.

Merchant derived the following well-known relationship by assuming that the deformation process adjusts itself to give minimum energy consumption.

$$\phi = \pi/4 - 1/2\,(\psi - \alpha) \qquad \text{........ 1}$$

It is assumed that ψ, α are independent of ϕ. Equation 1 does not fit in well with experimental data and Merchant (9) modified it by assuming that the shear stress on the shear plane is linearly proportional to the normal stress to give:

$$\phi = C - 1/2\,(\psi - \alpha) \qquad \text{........ 2}$$

where C is a material constant.

Lee and Shaffer (10) arrived at a different equation by applying the theory of an ideal rigid plastic body.

$$\phi = \pi/4 - (\psi - \alpha) \qquad \text{........ 3}$$

Neither theory gives a totally satisfactory explanation of actual cutting data. Other workers, such as Shaw et al (11), Oxley (12, 13) and Colding (14), suggest various shear angle relationships, but none of them has been found to be completely satisfactory either. In general, the shear angle relationship can be expressed as:

$$\phi = C1 - C2\,(\psi - \alpha) \qquad \text{........ 4}$$

where C1, C2 are constants depending on the tool-work pair (15). However, there are conflicting ideas about the actual shape of the plastic-flow region. Piispanen (16) Ernst (8) and Merchant (9) support the thin shear zone model. Palmer and Oxley (17), Okushima and Hitomi (18) propose thick deformation zone models, as shown in figure 2. Bitans and Brown (19) suggest that under different machining conditions the deformation approximates to one or other of these shear models. After examining motion picture film and photomicrographic evidence, they conclude that, especially when the metal is in an annealed state, the 'thick zone' model is more appropriate at low cutting speeds. At the high cutting speed region the situation approaches the 'thin zone' model.

2.3.1 TURNING PROCESS AND CHIP FORMATION

There are many methods of metal removal operation such as turning, milling, boring, drilling, facing, planing, forming and shaping, etc. Turning is the most commonly used of them all. Turning is an operation where a thin layer of the work material is removed from the surface of the workpiece material by driving a wedge shaped tool asymmetrically into it. As well as the generation of two new surfaces during the process, a thin layer of material is removed. This is called the chip or swarf and it passes on the rake face while moving in a direction away from the workpiece. The basic mechanism of cutting can be explained by analysing cutting with a single point cutting edge. The simplest case of this is known as ORTHOGONAL cutting in which the cutting edge is at right angle to the relative cutting velocity between tool and workpiece Fig 3. (ORTHOGONAL cutting - cutting edge perpendicular to cutting velocity). A single cutting edge inclined to the cutting velocity as in Fig. 4 (oblique cutting - angle of inclination of cutting edge) gives OBLIQUE cutting. Metal removed to form the fresh surface is plastically deformed to form the chip or swarf. The nature of chip formation is approximately the same for orthogonal or oblique cutting with one or more cutting edge. (20).

There are basically three different types of chips:Fig 5

2.3.1.1 DISCONTINUOUS CHIP

The discontinuous chip is one that separates into short segments which may or may not adhere to each other. It is usually produced when machining materials which have crack initiating phase (brittle) in them eg cast iorn. Distortion of the metal occurs adjacent to the tool face resulting in a crack at the head of the tool. Eventually, the shear stress across the chip becomes equal to the shear strength of the material, resulting in fracture and separation. With this type of chip, there is little relative movement of the chip along the tool edge. Discontinuous chips usually have a large chip thickness because of the inability of the material to withstand the large amount of strain which takes place in the shear plane in a very short time. This kind of chip has the practical advantage that it is easily cleared from the cutting area and occupies less room within the machine itself. Ductile materials can also produce discontinuous chips at low speeds and feeds.

2.3.1.2 CONTINUOUS CHIP (WITHOUT BUILT UP EDGE)

This type of chip produced when machining single phase materials or multi-phase alloys at high speeds and high feed rates due to the steady plastic deformation in the primary shear zone (21). The continuous chip is characterised by a general flow of the separated metal along the tool face. There may be some cracking of the chip, but in this case they usually do not extend far enough to cause fracture hence small chip thickness is very common here. This kind of chip is formed at higher cutting speeds when machining ductile materials. There is little tendency for the material to adhere to the tool, since there is minimum friction at the interfaces during machining. This results in a very smooth machined surface and polished tool face in addition to improved lubrication.

2.3.1.3 CONTINUOUS CHIP (WITH A BUILT UP EDGE)

This type of chip is produced when machining multi-phase materials at low speeds and feed rates. This kind of chip shows the existence of a localised, highly deformed zone of material attached or 'welded' on the tool face caused by high pressure and friction. Figure 5 shows three characteristic types of chip (22).

2.3.2 THE BUILT UP EDGE (BUE)

It has been observed that under certain cutting conditions and with multiphase work materials, a chip or part of it welded to the cutting edge. The presence of this welded material increases the friction between the chip and the tool, and in turn this friction leads to the building up of layer upon layer of chip material. The resulting pile of material is known as a built-up edge. Often the built-up edge continues to grow until it reaches an unstable point and then breaks down, the broken pieces being carried away by the underside of the chip and the new workpiece surface. Build-up edge formation in metal cutting is undesirable as it is one of the principle factors affecting surface finish and can have a considerable influence on cutting tool life.

2.4 SURFACE FINISH

In metal cutting machined surfaces are formed by the fracture under shearing stress. The new surface rarely originates precisely at the cutting edge of the tool (24). Wallbank (25) has shown that when a flow zone is present, the work material wraps itself around a sharp cutting edge and the new surface is formed where the work material breaks contact with the tool flank face, a short distance below the cutting edge. The contact between the flank face and the new workpiece surface is responsible for the surface roughness. Damage to the cutting edge results in a replication of this on the newly formed surface but the effect can be modified by further contact with the unworn flank face of the tool. The size, shape and distribution of micro-irregularities on the newly formed surface depends on the workpiece material as well as the extent of damage on the flank face of the tool. The surface finish surface is dependent on the feed and nose radius of the inserts. An increase in nose radius of cutting tools will result in an improvement of the surface finish generated (41). Excessive nose radii can give rise to vibration, which will result in rougher surface finish. A reduction in the feed rate will also improve the surface finish of the machined component. This will however increase cutting time thus affecting overall productivity. Cutting edge build up which forms at certain temperatures may also cause a rough finish. Each nose radius has a corresponding maximum feed which will produce the best possible surface finish. The appropriate values are readily available. The theoretical value of surface finish can easily be calculated from the following equation:

$H(theor) = S\,/8r$ where S = feed in mm/rev

r = nose radius in mm

2.4.1 MEASUREMENT OF SURFACE FINISH

In order to study surface finish and its effects on the performance of the product in operation, a number of quality control type instruments have been developed. These enable a check on tolerances to be made easily and the necessity of experience to be minimised. Some of these instruments may be used by unskilled and semi-skilled operators but those of more complex nature should be used by qualified operators.

There are many methods used for the measurement of surface finish. These include the use of stylus type instruments (Taylor-Hobson Talysurf), microscopic methods, brightness measurements and even some non-instrumental methods such as visual inspection or the use of a fingernail to trace across the surface. The latter is only acceptable in industries where the surface finish is thought to be of secondary importance.

The Talysurf is a system instrument which provides a wide range of parameters. It uses a processor to provide a selection of roughness and waviness parameters together with profile graphs. The measurement data is obtained via the movement of a stylus at constant velocity across the surface of the specimen. This movement is amplified electronically and the data automatically analysed. The parameter values are then selectable from the information. Some other measurement techniques are also available which are as follows:

a) Centre Line Average (CLA)

The CLA value is the standard adopted in Great Britain and since 1955, the USA. It is defined as an average height from a mean line of all ordinates of the surface regardless of sign. If an irregular surface is divided by its centre line then a number of areas are produced which can be measured by a planameter. Dividing the sum of these areas by the length of the sampling line gives a center line average. (Fig.6)

$$CLA = \frac{A1 + A2 + A3 + A4 \ldots AN}{L}$$

$$CLA = \sum A/L$$

where A = sum of areas above and below the mean line in mm.

L = length of trace in mm^2

b) Root Mean Square (RMS) value

This measure was standard until 1955 in the USA after which the standard was changed to CLA value. It is defined as the square root of the mean of the squares of the ordinates of the square measured from a mean line. (Fig. 7)

If equally spaced ordinates are erected at 1, 2, 3, ... n whose heights are h1, h2, h3 .... hn, then

h.r.m.s. = h1 + h2 + h3 + ... hn, then

h.r.m.s. = 1/L h dl

where h is an ordinate from the center line and L is a sampling length.

The information obtained from the Talysurf has the widest application in quality control in industry. The most common pieces of information used are the RMS and CLA values of the surface and these have been found to correlate well with a number of performance criteria. Graphical and representation of CLA and RMS are shown in Figs. 6 and 7. It must be noted that these are not the only ways of characterising surfaces and that others may prove more advantageous.

2.5 FORCES IN METAL CUTTING

Forces acting on the tool are an important factor within machining. The knowledge of these cutting forces is therefore essential for those involved with the manufacture and design as well as the purchase of machine tools. Cutting forces are also needed for working out power requirements and helps in determining the tool geometries. The cutting forces vary with the tool angles, and accurate measurements of these forces would be a helpful factor in optimising tool design.

For measuring the cutting forces to a considerable accuracy, many dynamometers have been developed and are now in use.

In non-orthogonal cutting, three major force components act on a cutting tool and those force components are represented by feed force(Fx),cutting force(Fz) and radial force (Fy). (See Fig. 8)

In the case of orthogonal cutting only two components Fz and Fx occur. The component of the force acting on the rake face of the tool, normal to the cutting edge, Fz is estimated to be the largest force component and acts in the direction of the cutting velocity whereas Fy which is the force which tends to push the tool away from the workpiece in a radial direction, is regarded as the smallest, and in semi-orthogonal conditions, usually ignored.

E M Trent (26) concludes in his stress analysis of metal cutting under seizure conditions that the contact area on the tool rake face is seen to be a most important region, controlling the mechanics of cutting. This is the reason for lower cutting forces for materials which have discontinuous chips.

It has been determined by many workers within this field that the cutting forces are directly proportional to the length of contact between the chip and the tool (25). This means that the materials producing discontinuous chips generate very low cutting forces. As the cutting speed increases there is a corresponding increase in the shear plane angle, which helps to generate thinner chips resulting in a considerable reduction in the contact length and hence cutting forces. The tool forces rise as the tool is worn out because the area of contact at the clearance face increases when the wear at the flank face progresses (26). It has been shown that when using carbide tools, the cutting forces decrease considerably when a jet of oxygen is sprayed at the tool clearance face (27). The reason for this is that oxygen helps to restrict the area of seizure thus resulting in a reduction of the cutting forces.

2.6 HEAT IN METAL CUTTING

During machining operations, high temperatures are generated in the cutting zone as a result of the chip formation process where the power consumed in deforming the work materials is largely converted into heat.

Increasing the metal removal rate above a certain limit produces a very high temperature which has a controlling influence on the rate of wear of the cutting tool as well as on the friction between the chip and the tool. The combined effect of the high temperature and the stress imposed on the cutting tool tends to cause the cutting edge to collapse.

Heat is generated in three major zones (28, 29, 30)

1. Primary shear zone.
2. The secondary shear zone.
3. On the flank face of the tool.

Fig. 9 shows the heat generation during orthogonal cutting in the turning operation. The temperature distribution in the primary and secondary shear zones depends on a great many factors. The nature of the workpiece is of particular importance, since its thermal properties play an important role in the heat generated. The tool/chip contact area also affects the secondary shear zone temperature. It has proved difficult to measure the temperature in metal cutting and to obtain the temperature gradients. Several methods of measuring cutting temperature (both average values and distribution) have been used. These can be categorised as follows:

a. Thermo - emf (thermocouples).

b. Radiation (pyrometer, infrared photography etc).

c. Thermo - chemical reactions (thermo - colours).

d. Constant melting point powders.

2.6.1 Heat in the Primary Shear Zone:

As reported by Taylor (31) the energy involved in plastic deformation goes largely into thermal energy. The extent to which this energy transformation occurs depends upon the strain energy involved in the process.

Under most machining conditions the largest amount of the work is carried out in forming the chip. The temperature of the chip can affect the cutting performance of the tool. However, some of the heat from the deformed layer of work material is conducted back into the workpiece and raises the temperature of the machined part. To summarise, most of the heat resulting from the work done on the shear plane to form chip remains in the chip and is removed from the cutting zone with the chip. Trent estimated that 99% of the heat generated in cutting was present in the chip (41).

2.6.2 Heat in the Secondary Shear Zone

The heat generated at the tool/chip interface is of major importance in relation to tool performance. Furthermore, it is particularly significant in limiting the rates of metal removed in cutting steels and other alloys of high melting point. The amount of strain in the flow zone near the tool surface are very large and are caused by what is known as seizure. The ability of metals to withstand such enormous shear strains in the flow zone without fracture must be attributed to the very high compressive stresses in this region. Compressive stress at the rake face decreases as the chip moves away from the cutting edge. The material from which the flow zone is composed changes continuously as new material is fed in near the cutting edge. It is continuously sheared as it flows over the rake face until it leaves the tool as a thin layer under the surface of the chip. Thus, unlike the material in the body of the chip, it is continuously being sheared and progressively heated by the work done and therefore, the temperature can be expected to increase as it flows away from the cutting edge. The tool thus acts as a sink into which heat flows from the zone while a stable temperature gradient is built up within the tool. The heat flowing into the tool from the flow zone raises its temperature which is the most important factor that limits the rate of metal removal when cutting the higher melting point materials.

2.6.3 Heat on the Flank Face of the Tool:

As shown in Figure 9, a third heat source would be present owing to friction between the tool and workpiece surface. In this case the clearance angle of the tool has an influence on the heat generated because if it is large enough it can ensure that separation of freshly cut workpiece surface is performed without rubbing against the tool face. However, a very large value of clearance angle is not recommended since it weakens the tool and therefore, a compromise value should be adopted. Furthermore, it bas been reported (32) that the temperature on the flank will also be influenced by the rake face temperature. However, if the tool is severely worn, the generation of high temperature in this region is usually followed immediately by the collapse of the tool.

2.7 CUTTING TOOL MATERIALS AND THEIR WEAR MECHANISMS WHEN MACHINING STEELS

The production and economic advantages of utilising the proper tool material in any machining operation are considerable. A great many companies have not changed their machining conditions over the years, even though cutting tools have greatly improved. Employing the wrong cutting speeds and feeds in an industry where billions of pounds are spent annually in cutting, is a costly matter. Undoubtedly, there are also appreciable losses in productivity and higher production costs as a result of the fact that a large portion of the industry does not use the new or right tool materials made available in recent years. Cutting tools are getting better. New and improved materials have replaced, or supplemented traditional cemented tungsten carbide and high speed steel cutting tools over a wide spectrum of metal cutting applications. Industry is increasingly recognising the importance of maximum metal removal rate which can form the starting point to understand the relationship between the low cost of the tool versus the high cost of direct labour. There has been a wide range of tool materials introduced to the market throughout the history of metal cutting. But those tool materials which have survived and are commercially available today, are those which have proved fittest to satisfy the demands put upon them in terms of the life of the tool, the material removal rate, the surface finish produced, the ability to give satisfactory performance in a variety of applications and the cost of the tools.

2.7.1 REQUIRMENTS OF TOOL MATERIALS

Tool materials must possess two basic qualities; sufficient strength to avoid tool failure by fracture and high wear resistance for increased accuracy and efficiency of machining (33). Trent (34) catalogues the parameters which tool materials should have:

1. High compression strenghnear the cutting edge. Therefore, the tool should have a much higher yield stress than the workpiece.
2. High tensile and shear strength.
3. The tool should be tough and be able to deform without cracking. They should possess adequate fracture toughness.
4. The tool material should be able to withstand steep temperature gradients and fluctuations (chemical inertness).
5. The tool must be abrasion resistant.
6. The tool must be able to withstand cutting with a built-up edge.
7. The tool should be resistant to attack by cutting oils and lubricants.
8. High hardness both at room and elevated temperatures.

In order to avoid failure, the strength and wear resistance are controlled by the above stated factors. The other factors that are important are:

a) Workpiece Variables

The properties of the work material are important in chip formation and have a large influence on both the nature and the rate of cutting tool wear. Small variations in the microstructure of the work material can cause considerable alterations in the cutting characteristics and in the overall performance of the tool. Concerning the work material variables, three factors are taken into account:

- the chemical composition
- the mechanical properties
- the thermal properties

b) Chemical Composition

To control the properties of the work material in order to improve the machining operations, the metallurgist can alter the microstructure and the matrix properties of the alloy either by adding free machining additives or by mechanical treatments, such as cold working and heat treatment. Empirical attempts to relate chemical composition to machinability have been made by a number of research workers (35, 36, 37). Boulger (35) evaluates the effects of carbon, silicon, phosphorous and sulphur on machinability. He reports a deteriorating effect on machinability as the silicon content of the steel increases. Paliwoda (36) and Schroder (37) gave statistical analyses of the observed machinability for a number of free cutting low carbon steels, which have minor differences in their chemical composition. They relate the percentage of the chemical constituents of the steels to the cutting speed to give a tool life of 60 minutes. Although the analyses show a linear trend, the results are scattered and cannot be explained in terms of chemical composition of the steels alone.

c) Mechanical Properties

The properties of the work material are important in chip formation. If the material exhibits high hardness and strength, resistance to plastic flow during machining is high. The combination of high hardness and resistance to plastic flow increases the specific power requirements during machining and the metal removal rates are then limited and relatively low. Tool wear increases due to the repeated contact of the cutting edge with a hard work material, as well as thermal softening and thermally activated wear accompanying high tool/chip interface temperatures. Several investigators reported a correlation between hardness and tool life (38, 39).

Work material ductility is another important factor in the machining process. Materials with high ductility permit extensive plastic deformation of the chip during metal cutting, which increases work hardening, heat generation and temperature. Furthermore, high ductility results in longer, 'continuous' chips that remain in contact with the tool face, for longer periods, thus causing more frictional heat. Moreover, the work hardening of the material is more important than the initial hardness in determining the power required and heat generated in the cutting zone.

d) Thermal Properties

It is widely accepted that the thermal properties of the workpiece material have an influence on the chip formation process. The coefficient of thermal expansion, thermal conductivity and specific heat properties play an important role in the local temperature produced in the cutting zone. High thermal conductivity of the workpiece material causes the chip to weld or adhere to the cutting edge of the tool, thus forming the built-up edge which affects the dimensional accuracy of the parts produced. Low thermal conductivity and specific heat, on the other hand, causes the heat generated to be carried away from the cutting zone through the chip produced, hence positively affecting the tool life. However, the coefficient of thermal expansion can have an unfavourable effect on the dimensional accuracy.

e) The Effect of Cutting Fluid

Cutting fluids are employed for two main reasons, namely to cool and to lubricate the cutting zone. This zone comprises the region of the tool cutting edges and the tool workpiece interface. During a machining operation the cutting tool induces a continuous wave of dislocations which travel ahead of the cutting edge, deforming and shearing the workpiece metal into continuous or discontinuous chips. The energy required for this deformation is primarily converted into heat. Simultaneously, frictional heat is generated at the point where the tool rubs against the new surface and the chip rubs against the cutting face of the tool. These combined effects raise the tool temperature to a level that might affect its life, since the wear mechanism of the cutting tool is temperature dependent. Consequently, using a cutting fluid for cooling purposes is often effective for improving tool life and the surface finish of the machined parts.

The aim of the lubricating action is to reduce friction between tool and workpiece, ie. to prevent adhesion by deliberately producing a mild form of corrosion. However, the effects of lubricants in machining are not yet fully understood, as their effects are different from those observed in conventional sliding experiments. This is because the lubricating action may accelerate the total rate of tool wear if the increase in corrosive wear offsets the decrease in adhesive wear (40).

2.7.2 WEAR MECHANISMS IN CUTTING TOOLS

Introduction:

It is generally accepted that tool wear is of crucial importance in metal cutting. It represents a major index of the performance criteria of a cutting tool. Since useful tool life is limited by wear. Acceptable surface quality and integrity, dimensional accuracy and consequently, the overall economics of machining are directly influenced by tool wear. Furthermore the continued development of new and sophisticated alloys, new cutting tool materials, NC and CNC machine tools present increasing problems that relate to the performance of tools and in particular, to tool wear.

The manner in which a tool wears, the part of the tool that wears most and a practical consequence of tool wear vary both with cutting conditions and with the quality specifications of the part being machined. As a result, the concept of 'tool life' can be interpreted differently in different contexts. Similarly 'wear rate' will have a different meaning for different people.

WEAR MECHANISM:

Failure in cutting tools is usually brought about by one or a combination of the following wear mechanism:

- Gradual wear
- Brittle fracture
- Plastic deformation

However, under properly controlled cutting conditions and with a proper selection of tool material, tool geometry, etc. a cutting tool usually fails as a result of gradual wear. That is, through progressive loss of tool material caused by mutual interactions between the tool and the workpiece, as well as between the tool and chips.

GRADUAL WEAR:

Current knowledge of the tool wear process indicates several basic types causing the tool to gradually wear away. These may be listed as follows:

- Abrasive wear
- Attrition wear
- Diffusion wear

2.7.2.1 ABRASIVE WEAR:

Abrasive wear is caused by the hard constituents of workpiece material, such as carbides, oxides and nitrides. These include fragments of built-up edge which plough into the tool surfaces as they sweep over the tool. The relative hardness of the two bodies in contact, the stresses acting on the sliding surfaces and the cutting media greatly influence the rate of abrasive wear. Although abrasion may be caused by hard inclusions Trent (41) reported the presence of ridges on worn tool surfaces emanating from wear resistant inclusions. These are in the surface of the tool and forces work material to flow around them cutting channels at either side of the ridge and giving rise to a scratched appearance which may wrongly be attributed to abrasion. Trent concedes that abrasion may possibly occur in the machining of a rough casting with trapped sand pockets or alloys which contain aluminium oxide.

Abrasive wear is unlikely to make a significant contribution under the vast majority of cutting conditions to the wear of carbide based tools as these tools are characterised by their high hardness relative to the work piece being machined. In general, the abrasive action is relatively more severe on the tool flank face because of the nature of the contact.

2.7.2.2 ATTRITION WEAR:

Attrition wear is the most dominant type of wear during the machining, if immature surfaces exist and there is a relatively small area of actual tool/work contact. It is particularly evident when cutting at relatively low speeds where temperature is not sufficiently high enough for wear based on diffusion to be significant.

During cutting the built-up edge changes continually with the work material being built on the cutting edge and with fragments being sheared away due to cyclic stress fluctuations (42). Attrition wear is a discontinuous process where whole grains or small aggregates of the tool are suddenly removed. It is an intermittant action dependent on fluctuating stresses and strains or the periodic attachment or detachment of the work material at the tool surface.

If only the outer layers are sheared away, while at the same time the part of the built-up edge adjacent to the tool remains adherent and unchanged, the tool continues to cut for long periods of time without wear. However, the shearing of interfacial weld areas leads to the plucking out of material from the tool. Subsequently, this is carried away by the newly created workpiece surface or the chip. Trent (43) mentioned that fragments are broken away because of localised tensile stresses imposed by the unevenly flowing material. Moreover, these tensile stresses may act where the strength of the tool constituents are low in relation to the bulk properties of the tool, which then results in an acceleration of wear.

Since the metal flow around the tool edge tends to become more laminar as the cutting speed increases, the rate of wear by attrition may increase as the cutting speed falls. Therefore, to improve tool life where attrition wear is significant, a rigid machine free from vibration and with adequate clearance angles on the tools should be used.

2.7.2.3 DIFFUSION WEAR:

If in metal cutting processes the machining is performed at a high speed and a high feed rate, the cutting temperature increases and a crater is formed on the rake face of the tool. It has been demonstrated (44, 45) that at high temperatures, diffusion mass transfer may take place at the interfaces, where the chips slide over the contact surface. This means that in favourable conditions of temperature and time atoms of different elements in the tool material are simultaneously introduced into the work material. However, Opitz and Konig (46) report that the effect of diffusion is not based on transfer of atoms, but on the formation of new complex carbides which results in the weakening of the microstructure. They proposed a model for diffusion processes as shown in Figure 10. In the case of high cutting speeds, an austenitic structure might be formed on the underside of the chips when machining steel. The complete solubility of the components, austenitic on the one side and cobalt or nickel on the other, makes it possible to form iron-cobalt or iron-nickel solid solution crystals. Iron diffuses into the cobalt phase and brings about two reactions which increase the rate of dissolution. In the first place, it may enter into complex carbides. Secondly, it increases the solubility of carbon in cobalt. This in itself is a required condition for initiating the dissolution process of tungsten monocarbide. Carbon set free in the dissolution process of tungsten carbide diffuses into the steel as may be seen in Figure 10. Various investigators would appear to have agreed on important points (46).

1. Diffusion of iron into the cobalt phase of the tool.
2. Diffusion of cobalt into iron forming a continuous solid solution.
3. Dissolution of tungsten carbide and the formation of double carbides.
4. Diffusion of free carbon in the tool in the direction of workpiece.

Cook (47) on the other hand reports that as a consequence of diffusion bringing about structural degradation of the tool surface, mechanical removal of the carbide particles subsequently take place. Trent (48) however, has not found any evidence for Cook's phenomenon.

Summarising, it has been established that at high temperatures, the wear rate of the cutting tool used at high speed is greatly influenced by the chemical stability of the tool constituents and by the relative affinity of both tool and workpiece materials.

2.7.2.4 FRACTURE:

Brittle fracture of the cutting tool has been regarded as one of the most serious problems in production. Brittle tool failure involves the development and propagation of micro-cracks in tool material. Micro-cracks develop at the so-called dangerous point when the stress state is such that it causes tool rupturing of the inter-atomic bonds. Generally, brittle fracture of the cutting tools is categorised into two types of fracture, namely the thermal fatigue and the mechanical fracture.

Thermal fatigue cracks rarely occur when turning, but are quite common when milling. These cracks are due to the fact that the cutting tool is subjected to the alternation of heating and cooling. As in the case of intermittent cutting action, temperature gradients are introduced into the surface layers (49), producing high tensile stresses which result in parallel cracks appearing in the tool approximately perpendicular to the cutting edge, but possibly inclined to the direction of the chip flow.

Cutting tools may fail mechanically as a result of chipping (gradual damage of the cutting edge) or of breakage (fracture of a large portion of the tool edge). The mechanical failure could be explained as follows. The relatively brittle carbide tools may deform plastically when the conditions of stress and temperature exceed the hot yield strength of the material. Any part extended above or beyond the surrounding surface or other adverse cutting geometry modification arising from deformation are easily chipped off the tool which may initiate a process of rapid edge breakdown (50). Mechanical fracture may be initiated by stress fluctuations which are due to machine tool chatter and workpiece discontinuities or inhomogenity. Chipping and fracture can also result from poor handling and lack of care in the setting up. Poorly designed tool holders can have the same effect if they fail to provide sufficient backing up support for the tool; thus allowing it to move or be subjected to bending moments.

2.7.2.5 PLASTIC DEFORMATION:

This form of wear or damage was first reported in 1907 in a comprehensive paper on metal cutting by Taylor (51). He stated that 'according to the part which heat has played in producing wear, worn out tools may be properly divided into 3 classes: wear of tools in which heat has been so slight as to have no softening effect upon the surface of the tool, and wear of tools in which the heat has been so great as to soften the tip surface of the tool beneath the chips almost at once, after starting the cut, and in which heat has played the principal part in the wear of the tool.'

Since Taylor's work, other studies (52, 53) have focussed on the deformation of the cutting tool as it takes place under high stresses and temperatures when cutting is performed at high speeds and feeds. The result of these investigations can be summarised as follows:

1. Failure due to deformation is more probable at high feed rate.

2. The plastic deformation mode of failure is more significant when cutting materials which are of high hardness.

3. Carbide grades with low cobalt contents can be used at high speed and feed rates because of their increased resistance to deformation.

4. Maximum deformation occurs predominantly at the nose of the cutting edge.

5. Deformation on the tool can be observed as a bulge on the flank and rake faces.

6. Fine grain alloys are considered to have greater resistance to plastic deformation (41).

2.7.2.6 TOOL WEAR PATTERNS:

The patterns of cutting tool wear vary depending on a great number of factors involved in the machining processes. These include tool material, work material, tool geometry etc. According to Venkatesh and Colding (54) the general forms of tool wear for different tool materials (such as carbide tool, high speed steel tools and ceramic tools) which may be produced gradually during the metal cutting processes are shown in Figure 11 (41).

Six basic forms of wear can be established:

1. Flank wear (wear land).
2. Crater wear.
3. Primary groove (outer diameter groove or wear notch.
4. Secondary groove (oxidation wear)
5. Outer chip notch.
6. Inner chip notch.

2.7.3 HIGH SPEED STEELS (HSS)

HSS tools were developed just before 1890 by F W Taylor. Since the Industrial Revolution up until the invention of HSS tools, there were only carbon steel tools and the only significant innovation had been the self-hardening steels initiated by R Mushet (55) in England in the 1860's. In 1906, Taylor (56) in his outstanding paper on the art of cutting metals, introduced the optimum composition of HSS tools as:

C - 0.67% W - 18.91% Cr - 5.47%
Mn - 0.11% V - 0.29% Fe - Balance

The optimum heat treatment was given as heating to just below the solidus (1250 - 1290 degrees centigrade), cooling in a bath of molten lead to 620 degrees centigrade and then to room temperature and tempering to just below 600 degrees centigrade. These tools were capable of machining steel at 30 m/min which was four times as fast as when using self-hardening steels and six times the cutting speed for carbon steel tools.

Tool steels have a high hardness due to the presence of martensitic structure. In the fully hardened condition, carbon steel tools have a maximum hardness of approximately 950 HV.

Today's HSS have a typical analysis of:

C - 0.75% W - 18% Cr - 4%
V - 1% Mn - 0.6%

Such HSS when fully hardened has a hardness of 850 HV. The alloying elements, tungsten, (W), and Vanadium, (V), tend to combine with carbon to form very strongly bonded carbides with the composites, Fe_3W_3C and V_4C_3. These carbides are harder than the martensitic matrix in which they are embedded. In heat treatment, they prevent the grains of steel from growing as these particles remain insoluble even up to high temperatures. These particles have a size of a few microns and are visible when viewed under a microscope.

It is for this reason that HSS can be heated to a temperature as high as 1290 degrees centigrade without becoming coarse grained and brittle. However, the outstanding behaviour of HSS is played by carbide particles formed during the tempering operation. These particles are only about 1/1000 of the size of visible ones (0.01μ m across).

This 'secondary hardening' is due to the formation within the martensite of these extremely small particles of carbide. The W and V from the high temperature treatment before hardening came out of solution and precipitated throughout the structure on re-heating to 400-600 degrees centigrade (57). The loss of strength and permanent changes in the structure of high speed steel when heated above 600 degrees centigrade, limits the rate of metal removal when cutting higher melting point metals and alloys.

There are different kinds of high speed steels available today. They can generally be divided into three basic performance groups (58). Recent developments with regard to composition of high speed steels has been geared towards the carbon content. This is sometimes reinforced with a cobalt additive.

High Speed Steels are classified into T-type and M-type depending on whether tungsten or molybdenum is the major alloying element in the steel. The T and M-types of HSS tools can be used interchangeably because of their similar properties and comparable cutting performance. Heat treatment of M-type steels usually require great care since they tend to decarburise more during heat treatment due to the narrow temperature range available for heat treatment. M-type tool steels are more widely used and are less expensive (about 30% less) than the corresponding T-type steels due to the greater availability and low cost of molybdenum and the fact that only about half as much weight of molybdenum as tungsten in an equivalent T-type is required to give the same properties and performance. The continuous development of high speed steels has been hindered by the increased use of sintered carbides which will be discussed later.

2.7.4 CEMENTED CARBIDES

The term 'cemented carbide' refers to the fact that a metallic carbide is actually bonded or cemented together with a matrix of a lower melting point metallic element. Very high temperatures made available by the electric furnace in the late 19th century gave rise to the production of new hard metals. Soon afterwards in the early years of the 20th century, tungsten powder was produced. In the early 1920's the carbide WC was produced in powder form with a grain size of a few microns. This was thoroughly mixed with a small percentage of a metal of the iron group - iron, nickel or cobalt - also in the form of fine powder. The mixed powders were pressed into compacts which were sintered by heating in hydrogen to above 1300 degrees centigrade. The product was completely consolidated by the sintering process and consisted of fine grains of WC cemented together with a binder. Cobalt was soon found to be the most efficient metal for bonding.

The primary features of carbides that makes them useful for cutting tools is high hardness, which allows carbides to cut metals and resist abrasion. They are strongly metallic in character having good electrical and thermal conductivities and metallic appearance.

There are four main grades of cemented carbide tools available:

1. Tungsten carbide/Cobalt alloys.
2. Cemented titanium carbides.
3. Mixed cemented carbides.
4. Coated carbides.

2.7.4.1 TUNGSTEN CARBIDE/COBALT ALLOYS:

The original and still the most basic, commercially available cemented carbides consist of fine, angular particles of tungsten carbide - the hard and abrasion resistant constituent - bonded with tough, comparatively soft, metallic cobalt. It is the proportion of tungsten carbide to cobalt that determines to a great extent the qualities of a cemented carbide. More tungsten carbide - a harder product, more cobalt - a tougher product. Tungsten carbide powder is by far the most important ingredient in cemented carbides representing 56-93% of the total. For the maximum hardness, the tungsten carbide grains should be as small as possible, preferably below one micron. Although tungsten carbide is ranked seventh in hardness on the list of nine (Figure 12) (59) it is still the top material used in cemented carbides. This is because it exhibits much greater toughness. Another very important property of WC is that it can be readily bonded with iron group elements most specifically cobalt, a fact that was discovered over 50 years ago. The melting point of cobalt is 1400 degrees centigrade but there is a WC - Co eutectic at about 1300 degrees centigrade that facilitates liquid-phase sintering.

Hardness and abrasion resistance increases as the cobalt content is lowered, provided that sufficient cobalt is present (1.5% would be enough) to ensure complete sintering. In general, as carbide grain size and/or cobalt content are increased, tougher and less hard grades are obtained. To attain optimum properties, porosity should be at a minimum, the carbide grain size should be as regular as possible and the carbon content of the tungsten carbide phase close to the value of 6.12% (60).

2.7.4.2 CEMENTED TITANIUM CARBIDES:

As a hard metal cutting tool material, the basis for the use of titanium carbide is that it is extremely strong. It has the highest hardness of any of the commonly available hard metal carbides, being at least 50% harder than the most used hard metal based tungsten carbide. In addition, titanium carbide is an essential ingredient in tungsten carbide base compositions when used for machining steel. Another important factor is availability which results in lower cost; titanium carbide is the ninth element in the earth's crust, whereas tungsten is the 59th. Two other factors which favour titanium carbide are first, the rapidly rising cost of cobalt and its limited availability and second, the cost of tungsten carbide which is essential in tungsten carbide base compositions used for steel cutting. Cemented titanium carbide had been applied primarily for machining steel because of its extraordinary crater resistance. It also showed remarkably good resistance to flank wear when cutting steel particularly at moderate to high speeds. The problems with cemented titanium carbide is its tendency to chip and break and its low abrasion resistance. The low thermal conductivity and low coefficient of friction results in a high chip curl and this causes a narrow crater close to the cutting edge of the insert, which often caused crater breakthrough. Another drawback of cemented titanium carbide was the tendency for depth of cut notching probably due to the lower oxidation resistance of this material as compared to the cemented tungsten carbide (61).

2.7.4.3 MIXED CEMENTED CARBIDES:

These grades are used for machining steels and other ferrous alloys. The purpose of the added TiC content is being able to resist diffusion wear which causes cratering. A solid solution or mixed crystal of WC in TiC retains the anti-cratering property to a great extent. Since TiC based solid solutions are considerably more brittle than the tungsten carbide, TiC content is kept as low as possible, sufficient to avoid severe cratering. An important difficulty with this grade is that high TiC cemented carbides readily absorb variable amounts of oxygen which cannot be reduced by hydrogen in the typical furnace atmosphere. It is, therefore difficult to hold the composition of these grades with any great precision as carbon is often lost in sintering.

WC/TiC/Co grades generally have two distinct carbide phases, angular crystals of WC and rounded TiC/WC mixed crystals. The carbon content of WC/TiC/Co grades is considerably less critical than with WC/Co types.

In the early days of carbide development, grades containing both tantalum and niobium were developed in opposition to those based on WC/TiC. Tantalum carbide does indeed resist cratering but at a far greater cost. It does however, when in mutual solid solution with WC, confer much improved properties at high cutting edge temperatures, especially where considerable shock is involved. Grades containing tungsten, titanium and tantalum carbides have been and indeed would have been the most popular class of hard metals were it not for the development of coated carbides. They combine and even improve upon most of the best features of the longer established WC/TiC/Co and WC/TaC/Co grades.

The micro structure of these grades depends largely on the manufacturing procedure. Even today, the expensive tantalum is frequently employed both wastefully and inefficiently (62). The rounded multi-carbide particules are preferably and more efficiently produced by simultaneous 'carbonising' rather than the much slower 'interdiffusion' of carbide mixture during sintering (62).

Tools of this grade can take very heavy cuts at high speeds on all types of steels as well as on cast irons and nickel-based super alloys. They do not however, have quite the resistance to abrasion of grain refined straight WC grades.

A recent innovation by Inco Europe Limited, UK, is to substitute a cobalt-ruthenium alloy for the conventional cobalt binder. This, particularly is the complex steel cutting grades and has the effect of substantially increasing toughness, tool life and cutting performance without any corresponding deleterious effect on hardness and other properties.

2.7.4.4 COATED CARBIDES:

Probably the greatest advance in the economics of engineering production in the past 20 years has resulted from the introduction of coated cemented carbides. These have produced possibly the biggest improvement in metal cutting productivity since the introduction of cemented carbides some sixty years ago. Coated tools last twice to six times as long as their uncoated predecessors when cutting cast iron, carbon and medium alloy steels, or alternatively the cutting speed and consequent production rate can be increased by a similar factor to maintain a given life.

TiC, TiN and Al_2O_3 are the most popular coating materials on the market today. A Ti(C,N) coating has also been developed to exploit the wear resistance of TiC coating and the crater resistance of TiN coating. HFC and HFN are two other coating materials that have been put into practice with a lesser degree of success than that of the above coating materials.

For a more advanced study a Ti(N,C,O) coating was chosen as a coating material for cutting tool inserts in Japan in 1976-77 by Toshiba (63) Tungaloy Co. It showed excellent cutting performance but has not as yet found any apparent success in the market.

In general, according to extensive recent investigations in the performance of coated carbides, the following are most apparent (41):

a) Suitable coatings could control wear and considerably improve the life of carbide tools, especially at high speeds and high production rates.
b) The problem of ETA phase has been minimised if not eliminated in modern coated tools.
c) A secondary coating of TiN over the TiC coating improves crater resistance but at the expense of more flank wear when compared with a single coating of TiC (64).
d) Thicker, uniform TiC coating improves wear resistance.

e) An excessively thick coating of TiC and TiN shows greater cratering resistance but reduced resistance to flank wear, indicating that TiN gives a much reduced diffusion coefficient, but is less resistant to chipping.

f) The mechanical properties of coated carbide tools depend not only on the composition and thicknesses of the coatings but also on the manufacturing techniques.

g) An alumina coating over TiC coating enhances wear and crater resistance appreciably.

2.7.5 CERAMIC TOOLS

2.7.5.1 Introduction:

With the development of more efficient and more rigid machine tools, the demand for a tool material which can cut at high speeds and feed rates has been increased. No single tool material provides the complete answer to all machining operations but there is no doubt that for certain cases, high hot hardness, chemical inertness and reasonable impact strength would be considerably advantageous.

Ceramic tool materials would seem to be the best choice for high speed machining because of their ability to retain physical and chemical properties at elevated temperatures. However, these tools have not been entirely successful in industry partly due to their brittleness and partly because of a lack of sufficiently rigid machine tools [illegible].

There have been many attempts to find new tool materials since the beginning of the Industrial Revolution. Al_2O_3 tools were considered for machining as early as 1905 in Germany and patents were issued in England in 1912 and in Germany in 1913 (65).

Apart from higher productivity, the fact that the price of tungsten is increasing and difficulties in acquiring hard metals has resulted in a search for material of higher availability for cutting tools.

Early investigations on ceramic tools included the evaluation of boron carbide, silicon carbide and aluminium oxide (Al_2O_3) in competition with cemented carbides for the machining of metals. Modern ceramic tools were developed simultaneously during the 1950's by several independent groups and pioneering work at the Rodman Laboratory of Water Town, Arsenal developed procedures for utilising these materials for cutting metal (66). Ceramic tools became commercially available in the United States in 1954. The Ford Motor Company was one of the first manufacturing industries to establish a high volume production application for ceramic tools in the United States.

Early ceramic tools tended to be weak and failures resulted from improper applications and the use of unsuitable equipment. It is also important to note that development of machine tools has always followed the development of new tool materials and more and more adequate machine tools which can provide rigid and vibration free machine tools while running and operating at high speeds. Subsequent years of development have led to a better understanding of the importance of microstructure on controlling mechanical properties. During the 1960's modified ceramic inserts processed by hot pressing instead of sintering referred to as cermets, were developed. These are basically composites of Al_2O_3 and TiC combinations. Sialon ceramic tools were developed during the late 1970's. These are based on solid solutions of metal oxides such as Al_2O_3, Y_2O_3, MgO, BeO and others in the β-Si_3N_4 crystal structure. Hence the name Si-Al-O-N based on silicon nitride-based materials with aluminium and oxygen additions. Roland and Heaton (67) at Kennametal Inc. noted that during the 1980's three major areas of change are likely to emerge which will profoundly influence metal working technology and ultimately productivity. These areas being; cutting tool materials, a systems approach to metal cutting and improved quality assurance. Fundamental to all these areas is the cutting tool material itself.

Trent (41) notes two factors which retard the application of high speeds in many machine shops.

(i) When cutting speeds are high, the time required to load and unload the work in machines may be quite a large proportion of the cycle time, hence no proportional reduction in total machining time is achieved.

(ii) The second reason is that difficulties such as chip control at high speed may become accentuated.

With improvements made in ceramic tools concerning their predictability and subsequent developments in machine tools and the application of manufacturing systems, approaches to metal cutting and development of automatic tool changing. A new horizon will be opened with further increases in machining speeds by many times, like the previous achievements with HSS and cemented carbide tools when they were first introduced.

Several factors have recently rejuvenated interest in the development and application of ceramic cutting tools. These include:

- Advances in ceramic processing technology.
- Rapidly rising manufacturing costs of products in general.
- Need to machine more increasingly difficult to machine work materials.
- Rapidly increasing costs and decreasing availability of tungsten, tantalum and cobalt - the principal and strategic raw materials in manufacturing of cemented carbide tools.
- Advances in machining science and technology.

2.7.5.2 TYPES OF CERAMIC TOOLS

There are three major categories of ceramic tool materials available today; the pure oxide, mixed oxide and the nitride ceramics. Alumina (Al_2O_3) is predominant in the pure oxide and mixed oxide ceramics while silicon is predominant in the nitride ceramics. It is therefore useful to classify ceramic tools into two categories; the alumina and silicon based materials.

2.7.5.2.1 The Alumina Based Ceramic Tool Materials:

These include Al_2O_3, Al_2O_3 + ZrO_2, Al_2O_3 + TiC, Al_2O_3 + TiC + ZrO_2, Al_2O_3 + TiN and the recently developed Al_2O_3 reinforced with SiC whiskers (68). Pure oxide (Al_2O_3) ceramic was first considered for machining operations in Germany as early as 1905, 25 years before cemented carbides were introduced. This was a relatively high purity tool in which pure alumina was densified in the presence of grain growth inhibitors (MgO, TiO etc). Mixed ceramics were introduced in the 1950's as one of a range of different approaches used to consolidate alumina to meet the stringent mechanical properties demanded in metal cutting. They may be classified into metal bonded and alloy tools (69). In metal bonded ceramics, alumina is bonded by one or more of the transition metals while in alloyed tools, various alloying components either result in secondary phases or remain in solid solution. Predominant in these were the development of additions of ZrO_2, TiC and TiN.

2.7.5.2.2 THE Si_3N_4 BASED CERAMICS:

These were developed in the late 1970's. They exist in two modifications, the - Si_3N_4 is harder than the 3-Si_3N_4. Both forms are hexagonal with slightly different lattice dimensions. The maximum theoretical density of Si_3N_4 cannot be achieved by conventional sintering techniques. This gives rise to two shaping methods known as 'Reaction Bonding' and 'Hot Pressing'. The -Si_3N_4 is formed during the nitriding of silicon at temperatures of up to 1300 degrees centigrade (ie. reaction bonding). It has a smaller yttria (Y_2O_5) content and a higher aluminium content. The 3-Si_3N_4 is a covalent solid, which contains a negligible amount of oxygen and is a well formed particulate crystal in contrast to the whiskers sometimes observed in the -Si_3N_4 (70).

2.7.5.3 METHODS USED FOR PRODUCING CERAMIC TOOLS

The early ceramics were produced by sintering almost pure alumina which was then cut to size and shape and subsequently polished. Sintering aids are always used to achieve high quality microstructures (ie. to retain small grain size while achieving high densities). The sintering aids can be divided into three categories; those which promote grain growth, those which have no effect on grain growth and those which retard grain growth (Table 1). Some sintering aids produce double functions during sintering (71). Those which promote grain growth (Ti, Nb, etc) also promote sintering and those which retard grain growth, retard sintering. Thus, there should be careful selection of grain growth inhibitors to prevent re-crystallisation and yet ensure full density. The properties of a sintered tool are also strongly dependent on the sintering temperature and sintering time. High pore density and fine grain powders (0.5 - 1 micron) are required to produce a good ceramic tool by the sintering process. Ceramic tools made from very fine powders usually produce a coarser final grain size than those made from coarser starting materials (72). The high temperatures involved during sintering will progressively coarsen the grain structure with deleterious effects on the mechanical properties of the tool material (73). The grain boundaries tend to migrate towards their center of curvature resulting in further increases of the large grains at the expense of the smaller ones which shrink. This process will also result in the entrapment of most of the residual porosity within the grains with only a relatively small amount on the boundaries making further densification extremely slow.

These early problems have resulted in a move towards hot pressing, hot isostatic pressing (HIP), cold pressing, and reaction bonding processes, as alternative methods of manufacturing ceramic tools. These processes achieved densification with reduced grain growth.

The hot pressing technique was developed by Deeley and others in 1961 (74) to overcome the problems of solid state sintering to full density of solids with covalent bonding. These materials have low self diffusivities at temperatures below that at which thermal decomposition is dominant. In this process sintering aids such as magnesia (Mg0) are used. The major difference between sintering and hot pressing is the application of pressure during the consolidation process. Hot pressing ensures rapid densification and generally results in higher densities and transverse rupture strength (TRS) (489-689MPa) of alumina ceramics in comparison to the TRS of those produced with the conventional sintering process (193-345MPa). The hot pressing technique also produces specimens with fine grain sizes because of the lower temperatures and times in comparison to conventional sintering. Structural changes during plastic deformation can result in residual stress in the hot pressed ceramic tool. Progressive stages in the hot pressing of powder compacts include (75) repacking, plastic flow, grain re-arrangement, stress enhanced diffusion and a final stage of stress enhanced diffusion related to a creep model of deformation. An oversized die made from mould graphite is used for the hot pressing operation to allow for shrinkage during sintering. The rate of pressing should be controlled, too fast a rate will not allow entrapped air to escape and the preform will disintegrate during stripping. An organic binder is added to the powder to provide internal lubrication between the powder particles during pressing, and to facilitate stripping of the pressed compact from the die. The furnace atmosphere during hot pressing is reducing due to the presence of graphite in the die. This is different from conventional sintering.

The hot isostatic pressing (HIP) technique was originally developed for the fabrication of nuclear fuel components and materials not readily produced by conventional routes. The process makes use of inert gas pressure at elevated temperatures for the solid state diffusion bonding and joining of components of various metals and ceramics. The process involves an isostatic pressurising medium where uniform pressure can be applied over the whole surface of the compact using hot pressurised gas channelled through an expendable impervious container. This leads to the deformation of individual particles and the promotion of interparticle bonding. Lower pressure is required to consolidate most structural materials by HIP than with conventional hot pressing techniques. High pressure is used in hot pressing since the material is pressed in one direction and pressure is often lost due to friction on the container side walls unlike the HIP method. The benefits of the hot isostatic pressing have been summarised elsewhere (76), but it must be noted that as a production process, costs can be extremely high when compared to the sintering method.

The reaction bonding process was first used on a small scale for the production of Si_3N_4 in the 1950's. The mechanism of reaction sintering is divided into two consecutive steps. The first is the diffusion of the nitrogen containing gas through a previously pressed porous compact of silicon particles. The second step being the subsequent chemical reaction between the gas and the particles to form Si_3N_4 in situ. Components produced by the reaction bonding process have a lower modulus of rupture and impact strength in comparison to the hot pressed process. This is largely attributed to higher densities achievable in the hot pressing action. The reaction bonding process was however, used due to the difficulty of forming components by sintering Si_3N_4 compacts at atmospheric pressure, since densification will not occur below the materials decomposition temperature.

2.7.5.4 PROPERTIES OF CERAMIC TOOLS

Ceramics represent a basically different class of cutting tool material with characteristically unique chemical and mechanical properties. Ceramic cutting tools are structural bodies with defined cutting edges which consist of non-metallic, inorganic materials. These materials fall within the classification of oxides, nitrides and carbides with metallic or semi-metallic elements. Generally, oxides, carbides and nitrides are particularly suitable for use as cutting materials because they distinguish themselves by their high hardness, excellent chemical stability and high compressive strength at high temperature. The room temperature hardness of fine grained alumina of high relative density which is used for cutting tools is in the same range as that of the cemented carbides, 1550 - 1700 HV (77). The room temperature uniaxial compressive strengths of 250,000 to 600,000 psi (77). Currently, commercially available ceramic tools have a transverse rupture strength of 800,000 to 120,000 psi.

Ceramic cutting tool materials exhibit the following properties; high compressive strength, high resistance to plastic deformation, high hardness and wear resistance and chemical stability. These properties enable them to be used for high speed machining where high temperatures are generated. Ceramic tools exhibit a compressive strength which varies a little with temperature unlike cemented carbides which show a rapid drop in the compressive strength at elevated temperatures Figure 13 (78).

Ceramic tools must be used with negative rake angles or rounded/chamfered edges during machining in order to compensate for their low tensile and shear strengths and to take advantage of their high compressive strength and wear resistant properties. Negative geometries are recommended because positive rake inserts cannot withstand the mechanical and thermal shocks during entry and exit from the workpiece (41). The use of negative geometry places the ceramic tool tip under compressive loading and suppresses tensile crack formation. It has been reported that these negative geometries can lead to favourable residual compressive stress in the workpiece and may result in high fatigue lives of the components machined by ceramic materials (79). Ceramic tools have higher hardness than cemented carbides and are much harder than tool steels at both room and elevated temperatures (Table 2). Their hardness explains why they resist abrasive wear more than carbides and tool steels and can machine materials like castings with a long tool life provided fracture can be suppressed.

2.7.5.5 Additives/Alloying Elements in Ceramics and their effect on the Properties

2.7.5.5.1 The Alumina Based Ceramic Materials

Alumina has an ionic rather than a metallic bond, and consequently, is an electrical insulator with poor thermal conductivity. The low toughness and tensile strength of alumina ceramic tools make them less able to withstand rapid fluctuation of temperature and stress during cutting. The addition of additives such as the oxides of Cr, Ti, Ni or refractory metals to pure alumina lead to a significant improvement in mechanical properties (80).

Conventional alumina ceramics usually have a high fracture tendency when used for machining superalloys. This problem is reduced by adding zirconia (ZrO_2) to the composition. ZrO_2 helps in retarding crack propagation by transforming from a metastable state to a stable state when a crack is initiated, thereby increasing the toughness of the cutting tool. The zirconia is constrained from transformation during cooling from the sintering temperature which introduces compressive forces into the structure (81). In use when a crack forms, the metastable tetragonal ZrO_2 transforms to the stable monoclinic structure with an associated volume change causing compressive stress at the crack tip preventing propagation (82). These stresses effectively increase the fracture toughness of the material by about 20-25%. The ZrO_2 also enables the tool to withstand high cutting temperatures helping to prevent plastic deformation or oxidation wear. The improved fracture toughness makes a pure alumina ceramic tool suitable for some interrupted cuts and other difficult machining conditions which would not be possible without the zirconia addition.

Rapid temperature changes at the beginning of a cut or by use of coolants can cause fracture by inhomogenous thermal expansion at the cutting edge, this is known as thermal shock. The thermal shock resistance of ceramic tools can be improved by the introduction of a phase with a metallic nature. TiN and TiC are added to provide adequate edge strength and high resistance to thermal shock. The high thermal shock resistance of mixed ceramics enable them to be used for effective machining with or without coolants. The addition of TiC also results in a significant increase in the hardness of mixed oxide ceramics. The addition of SiC in the case of the latest Al_20_3 + SiC ceramic results in higher strength and an improvement in the fracture toughness of the brittle alumina matrix (68). Table 3 shows the properties of the pure alumina (Al_20_3 + $Zr0_2$), mixed oxide (Al_20_3 + TiC) and the nitride (Sialon) ceramics.

2.7.5.5.2 Silicon Nitride Based Ceramics

These tool materials have many good characteristics at high temperatures (1200 - 1400 degrees centigrade) eg. good oxidation resistance, good mechanical strength, chemical inertness and high hardness in comparison to alumina based ceramics. The high thermal shock resistance of Si_3N_4 based ceramics is a result of their good thermal conductivity and low coefficient of thermal expansion (Table 3). These two factors reduce the stress set up between the hotter and cooler parts of the insert. The Si_3N_4 based ceramics have very good edge strength because of this. However, chemical stability and wear resistance of Si_3N_4 based ceramic tools are somewhat lower than alumina based ceramics. Si_3N_4 is one of the tougher ceramics available. Their high fracture toughness make them less prone to catastrophic failure and encourages machining at higher feed rates than with alumina based ceramics. Reaction bonded Si_3N_4 has low strength due to increased pore space in the compact. The hot pressed Si_3N_4 components are theoretically fully dense; this improves their properties considerably. However, the pressing operation at high temperature limits them to fairly simple shapes. The advantages of sialon materials over conventional Si_3N_4 are improved resistance to oxidation, creep, and abrasion (82) and a pressureless sintering technique. The crystal structure consists of the 3-Si_3N_4 cemented by a glassy phase. The interlocking nature of elongated 3-Si_3N_4/Sialon grains contributes to the toughness of silicon nitride ceramics. However, the fracture toughness of Si_3N_4/Sialon materials does not approach that of cemented carbides.

2.7.5.6 Behaviour of Ceramic Tools in Machining

Ceramic tools fail mainly by wear on the flank face caused by the movement of the newly cut surface of the workpiece against the cutting tool. The rapid flank wear is often caused by the dislodging of individual particles from the matrix of the tool by localised stress concentration during the machining operation. The high temperatures generated during the machining operation may also encourage the development of an uneven stress region on the tool which will lower the cohesive strength of the ceramic bond. The severe wear on the flank face of the cutting tool can lead to the elimination of the clearance angle, which then becomes a heat source increasing the temperature and compressive stress at the tool nose resulting in the fracture or catastrophic failure of the tool. Flank wear is also caused by the inherent brittleness of ceramic tool materials which encourages the chipping/plucking of tool particles at the cutting edge (ie. attrition wear). Chipping can result if there are hard spots or inclusions in the workpiece material. Plucking of tool particles may also occur if the temperatures generated at the cutting edge are high enough to cause a reduction in properties of the interparticle bonds or when sufficiently high stresses result from the cutting action. The chipped off or plucked tool particles may travel down the flank face (or less likely, but possibly over the rake face) causing increased flank wear (83).

Rake face wear (cratering) occurs but it does not limit the tool life of ceramic materials. The crater is as a result of the chip flowing over the tool surface. The chemical stability/inertness of ceramic tools at high temperatures ensures that there is only a slight weakening of the interparticle bonds and minimal diffusion resulting in the small amount of cratering. Pure alumina ceramics show less crater wear than the mixed oxide (Al_2O_3 + TiC) ceramics when machining steel or materials with high iron content (84). This is probably because the mixed oxide ceramics contains TiC which has relatively more affinity for iron rather than the Al_2O_3.

Ceramic inserts can also fail by plastic deformation, fracture and notching. Notching at the tool nose and the end of depth of cut may either be due to chemical reaction at the periphery of the tool/chip interface where sliding conditions are dominant or by work hardening of the work material as a result of the high pressures at the tool/workpiece interface (83,85). Notching is a very critical wear process when machining heat resistant steels, nickel and titanium alloys with ceramic tools since these work materials generate continuous chips whose edge makes a fluctuating contact with the tool and also generates fluctuating stresses (86). This condition leads to the intermittent seizure (or contact) of the chip to the tool in very short time increments (about several thousand times a second). The release of the chip after the momentary seizure may lead to the pulling out of small fragments of the tool material. Premature failure or fracturing of ceramic tools can occur when cutting mainly at lower speeds because of their poor toughness and transverse rupture strength. This failure mode can also occur when cutting at high speeds due to a reduction of the chip/tool contact length and the uneven stresses acting at the edge. This is disadvantageous since a relatively small area will be heated up during the machining operation leading to the weakening of the tool and resulting in its premature failure.

Extensive research work has been carried out on the failure modes and wear mechanisms of sialon materials when cutting various work materials (87,88,89). Notching and flank wear are the major failure modes when cutting various materials (eg. nickel and titanium alloys, steel and cast iron). The notching tendency, mainly on superalloys can be minimised by using sialon tools with the appropriate geometry and employing careful machining practices. The selected tool geometry includes a 45 degrees approach angle. Sufficient clearance angle should be used to prevent the tool from rubbing the workpiece and dwelling in the cut. Wear mechanisms involving the reaction of the sialon material with the atmosphere particularly nitrogen have been proposed to explain notching when machining high nickel alloys. For flank wear diffusion of tool and workpiece materials to form spinels which are easily mechanically removed has also been proposed.

Plastic deformation of sialon tool materials can occur as a result of high compressive stresses during the machining operations and this can lead to cracks because of the tensile stresses around the cutting edge. These cracks have a tendency to open up very quickly as cutting proceeds resulting in the catastrophic failure of the tool edge. Sialon materials however, are not subject to the same catastrophic failure modes often seen with alumina based materials and can be utilised with coolants. These materials have found applications in machining Nickel based superalloys and cast irons but have not had any success with machining steel. This may be due to solubility of iron in the glassy phase of the ceramic lowering its glass transition temperature and thus altering the mechanical properties.

2.7.6 DIAMOND TOOLS

Diamond is the hardest of all known materials with a Vickers hardness number of 6000 at room temperature. It has poor toughness and is prone to chipping and fracture. It is not widely used as it is very expensive. To overcome the problems associated with brittleness and expense, synthetic diamonds were developed at the General Electric Company in the mid 1950s and the subsequent development of polycrystalline diamond (PCD). Polycrystalline diamond tools are aggregates of randomly oriented particles which behave as an isotropic material in many applications. This is unlike natural diamond which has only one large crystal with very severe problem of cleavage or fracture. The basic structure of the tool is a laminated one with a dense layer of synthetic PCD bonded to a tungsten carbide (WC) substrate with the aid of an intermediate refractory metallic bonding layer. It was possible to make tips with a body of cemented carbide and a layer of synthetic diamond particles approximately 0.5 - 1mm thick, sintered together and bonded onto the rake face of the tip. These are commonly known as polycrystalline tools. These cutting tools have been said to be successful in cutting Al-Si alloys (90).

Some pronounced features of diamond tools include:

i) High hardness, the high hardness of diamond is the most important feature of diamond tools used today.

ii) High abrasion/wear resistance.

iii) Very low coefficient of friction.

iv) Low coefficient of thermal expansion.

v) High thermal conductivity.

vi) Ability to form a sharp cleavage.

vii) Ability to maintain a sharp edge for a long period of time especially when machining soft materials like copper and aluminium (91).

Some disadvantages of diamond tooling include extreme brittleness; single crystal diamond has low impact resistance and cleaves easily. Because diamond is so brittle, tool shape is important. Low rake angles are normally used to provide a strong cutting edge. Diamond tools have a tendency to revert to graphite and/or oxidize in air at elevated temperatures (beyond 700 degrees centigrade). Wear in diamond also takes place by micro-chipping due to thermal stresses, oxidation and transformation to carbon due to frictional heating.

Diamond tools are very expensive. The use of diamond as a cutting tool material is however, restricted to operations where other tool materials cannot perform effectively because of its very high cost. Diamond tools cost about 20 - 30 times more than cemented carbide tools. Some difficulties are encountered in shaping and resharpening diamond tooling after use, more than in carbide tools.

2.7.7 CUBIC BORON NITRIDE TOOLS (CBN)

Cubic boron nitride (CBN) was developed in the late 1960's shortly after the development of synthetic diamond. This tool material has a hardness next to that of diamond. CBN can be synthesised and bonded at ultra high pressure to the surface of cemented carbide for use in metal cutting. It is much more stable than diamond at temperatures of over 800 degrees centigrade and reacts less readily with iron, nickel and their alloys (92). For the most creep-resistant nickel alloys, permissible cutting speeds with carbide tools are very low and machining costs are therefore, extremely high. When using cubic boron nitride, good tool life can be achieved when cutting the same alloys has been demonstrated at high cutting speeds. CBN inserts also cost in the region of 20 - 30 times the price of cemented carbides.

The structure of the tool is a laminate where a layer of polycrystalline CBN is bonded to tungsten carbide-cobalt (WC - Co) substrate. The laminate provides strength and resistance to shock and also allows flexibility in both handling and standardised tool holding. The primary application areas for CBN have been in hardened steel and high temperature alloy components. Krumrei (93,94) has described the productivity increases which were realised in machining hardened steel rolls with CBN tools. The effective use of silicon nitride tools for machining grey cast iron demands much higher cutting speeds. These higher speeds also make it possible for CBN to be more effective in machining cast iron.
However, the use of CBN tools in grey cast iron machining is limited to certain grades depending on their microstructure.

2.8 STEELS

Steel is an alloy based on iron and carbon and is one of the most commonly used materials in the manufacturing industry. Pure iron has little practical application except in special transformer cores, where it has high permeability if the carbon has been removed by moist hydrogen treatment (95). For all practical purposes pure iron contains carbon and small amounts of several other elements (eg. Ni, Mn, Si) and as such is known as plain carbon steel. Although the number of steel specifications runs into thousands, plain carbon steel accounts for more than 90% of the ductile and cheap material with reasonable casting, working and machining properties, which is also amenable to simple heat treatments to produce a wide range of properties. Unfortunately, it has poor atmospheric corrosion resistance. To understand the properties of steels it is necessary to consider the influence of the various alloying elements of which carbon is the most potent. Other alloying elements have secondary influences on properties depending on their quantity in plain carbon steels (eg. chromium, vanadium, cobalt, silicon, copper etc.). They are present as a result of pick-up from scrap, pig iron or de-oxidizers during manufacture. Manganese is added to the ladle to de-oxidize the steel but also reacts with sulphur to form a harmless globular MnS. Silicon is also used as a de-oxidizer and has little other effect.

Copper and tin are becoming increasingly more important as they are not removed in the refining stage, and modern usage of large amounts of scrap is gradually increasing the quantity of these two elements throughout the steel industry.

Aluminium is used to "kill" steels and also to produce stabilized non-ageing steels. It has been stated that these relatively simple steels, relying principally on carbon (up to 0.6%) to give their various properties, account for the vast majority of all steels in use today (96).

2.8.1 ALLOY STEELS:

Plain carbon steels, although widely used, are not adequate for all the requirements of modern civilization. They fall short especially with respect to strength at low and high temperatures, corrosion resistance and ability to harden uniformly (97). This is why special alloying additions have to be made to the steel in order to satisfy specific requirements. The addition of special alloys tends to increase the overall cost of the steel. The important alloying additions are nickel, chromium, manganese, molybdenum, tungsten, niobium, vanadium, cobalt, silicon and copper. These alloys may be added in various combinations to satisfy fabrication or service requirements.

2.8.2 TYPES OF STEELS, THEIR APPLICATIONDS AND MACHINABILITY

SILICON STEELS:

Silicon is present in all steels in residual amounts from the original iron and is also used as a de-oxidizer. However, it also has a number of useful alloying properties which are commercially exploited. Silicon shows useful solutions to hardening effects and is used in certain cheap low alloying steels (98). It also promotes resistance to high temperature oxidation and is often present in complex creep resistant steels. A major drawback of silicon addition is its graphitizing tendencies and, in such steels, strong carbide formers must also be present. An advantage may be taken of this tendency in high carbon steels which may result to precipitate graphite, giving good machinability.

MANGANESE STEELS:

Apart from its use as a general scavenger, manganese stabilizes the carbide phase as (Fe,Mn) C and also strengthens and toughens the ferrite while simultaneously reducing diffusion rates and making the transformation more sluggish (99). This has two important results; firstly, low alloy manganese steels have deeper hardenability than plain carbon steels, resulting in the inexpensive 1-2% manganese high strength structural steel;

secondly, it is easier to retain austenitic structures in the higher manganese steels. The best known steel containing manganese as the major alloying addition is Hadfields manganese steel. This alloy contains approximately 13% manganese with over 1% of carbon (100).

NICKEL STEELS:

Nickel behaves in many respects similar to manganese; but unlike manganese, it promotes graphitization of carbide on annealing. To offset this harmful effect it is necessary to add manganese or chromium. Nickel also improves the oxidation resistance; in fact, the high nickel austenitic steels have been used as gas turbine blades with some success (101).

CHROMIUM STEELS:

Chromium is a strong ferrite stabilizer and carbide former. It forms several carbides depending on the treatment and amount of chromium present; below 2% the chromium replaces iron in $(Fe,Cr)_3C$, but this changes to $(Fe,Cr)_7C_3$ and then, near 10% chromium $Cr_{23}C_6$ occurs, this being the characteristic chromium carbide in highly alloyed steels. These carbides are hard and stable, inducing wear and cutting ability as well as high temperature strength.

Small amounts of chromium improve properties of heat treated carbon steels and diminish the tempering rate. With about 0.6% carbon such steels are used for springs and gear wheels while with high carbon contents, to give more dispersed chromium carbides, they make good file and chisel steels (102). Further increases of carbon to 1.5% gives the normal ball bearing steel with its characteristic hardness, wear and corrosion resistance. The outstanding characteristic of chromium steel is of course its corrosion resistance; medium chromium (about 6%) steels with low carbon for ductility are used widely for fittings and pipes in the petroleum industry.

VANADIUM STEELS:

Vanadium is an expensive material and its use in steels has to be justified. Being a more reactive BCC element than chromium, it is a strong carbide former and ferrite stabilizer. The stable carbide V_4C_3. remains finely dispersed even at high temperatures, thereby limiting grain growth and giving thermal stability. Like the other high melting point metals, it facilitates heat treatment procedures and strength properties without affecting ductility. It is added in small percentages to tool and high temperature steel.

COPPER STEELS:

The use of copper in steels goes back more than a century ago but probably because of the hot shortness it can impart, it has never been allowed to realize its full potential. In steel casting the over-riding advantages of this alloying element are; an increase in fluidity of the melt, an improvement in atmospheric corrosion resistance and the ability by age hardening, to produce high strength steels. Copper is also added to some special steels such as the austenitic stainless variety, where it may partly replace nickel and increase the mechanical properties and corrosion resistance to certain media.

COBALT STEELS:

Cobalt is an enigma with regard to its behaviour in steels. It is the only transition metal which dissolves in austenite while reducing hardenability. It is missing from austenite and dissolves extensively in ferrite; it does not form intermetallics nor does it have a strong tendency to carbide formation. Nevertheless, it induces high temperature strength in both ferrite and austenitic steels and facilitates ageing treatments. The main uses of cobalt are partly limited by its cost to tool steels and complex creep resistant steels.

2.9 MACHINABILITY OF STEELS

Machining is one of the major, if not the most important manufacturing steps in the production of useable parts. The contribution of the machining operation to the total cost of manufacture is between 40 - 70% for parts such as connecting rods, transmission shaft and steering (103). The total cost of machining has been estimated in one study as $125 billion (104). Thus, any improvements in a steel's machinability has significant impact on the cost of manufacture. Not surprisingly therefore, machinability of steel and its improvements have been studied for a very long time. Any discussion of machinability must begin with the statement that machinability is not a unique material property which can be clearly defined and measured. Rather, machinability is a system property depending on complex, dynamic interactions between the work material, the tool, the lubricant and the machining condition (105). As a result, there are many different criteria for machinability and the same material may have different machinability as the operations (and hence the criteria) change. To deal with this complex situation, the commonly adopted approach is a separate examination of several machinability aspects. Improvements in machinability are characterised by one or more of the following: Increasing tool life, raising the rate of metal removal, improving surface finish, promoting easier chip removal and reducing cutting forces and power consumption during machining. A material is said to have good machinability if low power is consumed during the machining operation with low tool wear, the material producing a good surface finish without surface damage. Chip curl is an additional parameter included in machinability parameters; material which produces continuous chips are therefore less machinable than those which produce discontinuous chips.

The effects of some alloying elements on machinability of steel eg. lead which has been added since the 1930's to further improve machinability (106). However in the 1970's there were increased concerns with the toxicity of lead. The concern is not so much with the fumes of lead during machining, as several studies have shown that not to be significant, but with the emission of lead fumes during manufacture during reheating and hot forging as well as lead in the machine lubricant and subsequent processing of leaded chips.

Lead improves machinability by a two-fold mechanism. First, it reduces the energy through the formation of a liquid lubricant layer at tool-chip interface (107). Second, lead is a potent liquid metal embrittler and in combination with it acting as a crack initiator, it reduces the energy necessary for deformation and fracture (108). In the search for an alternative, it was noted that bismuth possesses many characteristics common to lead. It, like lead, is soft and has practically no solubility in solid steel. It is also a low melting metal and has liquid metal embrittling effects stronger than lead (109). It is also surface active and wets steels easily.

2.9.1 EFFECT OF ALLOYING ELEMENTS:

The deleterious effects of hard, abrasive oxides on machinability is well known. Calcium deoxidised steels are essentially of two kinds; the coarse grained, Si killed steels and the fine grained AL killed steels. In the former, the non-metallic inclusions are controlled to specific compositions in the CaO-

$MnO\text{-}SiO_2\text{-}Al_2O_3$ (110). These inclusions then deposit as layers on the cutting tools when machining at speed, and thus temperatures are high enough to soften these oxides. The tool life of gear cutters has been improved by as much as 70-100% by using calcium de-oxidized steels. With respect to other properties such as tensile strength, ductility, impact values and fatigue resistance, calcium containing steels exhibit behaviour similar to conventional steels (111).

The alloying elements such as carbon, manganese, chromium, etc. which are added to iron to produce steel, as well as increasing the strength of the material, also influence both the stresses and the extent of temperature generated. When cutting steel, the stress required to shear the metal on the shear plane to form the chip is greater, but the chip is thinner, the shear plane is larger and the area of the shear plane is much smaller than when cutting cast iron (41).

A very high percentage of all cutting operations on steel are carried out using high speed steels or cemented carbide tools. In order to achieve higher removal rates, steel work materials are heat treated to reduce the hardness to a minimum. The heat treatment for medium or high carbon steels often consists of annealing just below 700 degrees centigrade, which is the transformation temperature to spheroidize the iron carbide (41). However, it is important to note that when steels are heat treated to high hardness and to high strength, the compressive strength imposed on the tool during cutting may become large enough to deform the cutting edge and destroy the steel.

It has been found that the finer the grain structure of cutting tools the better the machinability of steel. There is a general reduction in the tool wear with fine grain structured tool (112). Research carried out indicates that chemical composition of the tool is generally an important factor in tool wear. It is known that, in the case of machining steel with carbides, the addition of titanium and tantalum carbides to tungsten carbide, reduces tool wear. This is not due to the greater hardness of these carbides, but can be mainly attributed to the chemical effects when in contact with steel at high temperatures (113). At high speeds, the sliding wear of ceramic tools is accelerated by local fracturing in addition to plastic deformation. Ceramic tools may also wear by diffusion wear mechanism which is a slower process where iron oxide (FeO) and Al_2O_3 interdiffuse. Also it is stated that ceramic tools can offer better resistance to oxidation, notching and grooving wear than cemented carbides. (114,115)

Lumby (116) claimed that sialon could be used successfully to machine mild, medium carbon and high carbon steel. In particular, it was reported that EN31 in the hardened condition (60 RC) could be machined in conditions where carbide and coated carbide failed at the moment of contact between the tool and the workpiece. Jawaid and Bhattacharya (7,117) machined a medium carbon steel, EN9 and compared results with coated carbide. Under similar conditions the coated carbide tool life of 8 - 15 minutes was increased to 25 minutes when sialon tools were used.

CHAPTER 3

3.0 EXPERIMENTAL TECHNIQUES

3.1 INTRODUCTION

Steel was chosen in this project because it covers approximately 60% of today's metal market. The machining of these materials is mainly carried out using carbide tools (which covers 80% of the cutting tool materials market).

The range of steel work materials were chosen that contain different percentages of carbon and also different alloying elements eg. EN8 (BS970, 1972, 080M40, 40% carbon steel), EN24 (BS970, 1970, 817M40) and D2 Tool Steel (K.E.A.180, BS4659 type BD2).

The use of ceramics for the machining of steel is very limited due mainly to the problems which are generated when ceramics are used for the machining of steels (ie. short tool life, unpredictable performance, etc).

With the ever increasing use of more rigid NC/CNC machines, ceramic tool materials have started to find more use in industry. Therefore, this project was selected in order to investigate the use of various grades of ceramic tools; namely KO60 (oxide based ceramic), KO90 (mixed ceramic) and KY2000, KY2500 and KY3000 (nitride based ceramics) which are manufactured by Kennametal Inc. for the machining of widely used steels.

Simple non-orthogonal turning without the use of cutting fluid was carried out. Speeds of 50-700 m/min in increasing steps of 50 m/min were used. The depth of cut and feed rate were kept constant throughout the tests.

Feed rate	:	0.16 mm/rev
Depth of cut	:	2 mm

The aim of this project is to determine the optimum cutting conditions, conditions at the tool workpiece interface, effect of cutting conditions on the rate of tool wear, tool failure modes and wear mechanism for each of the ceramic tool used. To achieve this, machining tests were carried out to determine tool life at various speeds using a set criteria. This was followed by the examination of the worn tools in order to observe the failure modes and wear mechanisms and how these were affected by the nature of the workpiece, tool materials and variables such as cutting speeds. Further investigations were carried out to determine the rate of wear and the conditions at the tool/chip interface through the measurements of cutting forces, the examination of the chip and the measurement of surface finish generated on the workpiece material.

3.2 MACHINING OPERATION

The experiments were carried out on a CNC lathe, Torshalla S250, without the use of coolants. The lathe has a variable speed range of 40-2800 rpm. This was advantageous as a constant speed could be maintained at different bar diameters, however to confirm a constant speed a tachometer was used. The workpiece materials were in the form of cylindrical bars. The bars were discarded when a 10 : 1 ratio was reached between the length and diameters. Ceramic indexable inserts of ISO designation SNGN 12 04 16 were used for all machining tests. The inserts were clamped mechanically in rigid tool holders which were themselves held in rigid tool posts. The inserts were clamped in a Kennametal tool holder to provide the following geometry:

Approach angle	:	45 degrees
Side rake angle	:	-6 degrees
Back rake angle	:	0 degrees
Clearance angle	:	5 degrees

Five kinds of ceramic tools as supplied by Kennametal Inc were used in this project:

i) KO60 (oxide based ceramic)

ii) KO90 (mixed ceramic)

iii) KYON 2000 (nitride based ceramic)

iv) KYON 2500 (silicon carbide whisker reinforced ceramic)

v) KYON 3000 (nitride based ceramic)

Cutting was interrupted every 2-5 minutes (and in some cases in a matter of a few seconds) and measurements were recorded; the inconsistency of stoppage time was due to very quick tool failure in some cases.

3.3 TOOL LIFE CRITERIA

Tool life criteria for ceramic tools were selected through the ISO recommendations (118,119) and also on the basis of previous work carried out on ceramics within Warwick Manufacturing group (7). The criteria were based on rejecting a tool when:

1) The average flank wear reached 0.4mm or maximum flank wear reached 0.7mm.
2) The notch at the depth of cut reached 1.00mm.
3) The crater depth reached 0.14mm.

4) The surface finish on the work material exceeded 6 μm (microns) on center line average.

5) When flaking or fracture occurred.

The tools were examined after known intervals. The width of the flank wear land was recorded using a travelling microscope. In cases where fracture was observed, machining was stopped and the cutting edge discarded.

3.4 MEASUREMENT OF SURFACE FINISH

Surface roughness was recorded using a portable stylus type equipment, ie. SURTRONIC 3. The average surface roughness value (Ra) was measured perpendicular to the feed marks an average value was recorded after three reading were taken. A major advantage in using SURTRONIC 3 was that the surface roughness could be measured on the machine without the need for removing the work material for every reading. SURTRONIC 3 was calibrated before each set of readings was taken.

3.5 MEASUREMENT OF CUTTING FORCES

The cutting forces were measured using a KISTLER Piezo electric dynamometer type 9263. This equipment was used to measure three component forces on the X, Y and Z directions. During the process of machining, cutting forces acted on the tool holder which was clamped onto the dynamometer. These forces were converted into a voltage by the presence of the Piezo electric crystals and fed into the charge amplifiers which were connected to a chart recorder enabling the signal to be recorded. In this investigation, only two component forces were measured ie. cutting force (Fz) and the feed force (Fx).

3.6 EXAMINATION AND MEASUREMENT OF WORN AREAS

After every stoppage the edge of the tool insert was washed in a diluted hydrochloric acid (10% HCL) for at least two minutes to remove the adhering metal on the rake and flank faces of the tool. Average flank wear, maximum flank wear, and notch depth were measured using a travelling microscope.

3.7 THE QUICK STOP TECHNIQUE

This technique is used by stopping the cutting action suddenly which enables the examination of the chip flow pattern under the actual condition of cutting.

For this procedure, a humane killer gun was used, the gun was fired, on firing the bolt of the gun which strikes the tool breaking the shear pins which holds the tool in position during the machining processes. Sudden breakage of clearance of the tool freezes the chip formation process. Usually, the tool comes away more or less cleanly with the chip attached to the bar. The segment of the bar with the chip attached was cut out mounted and examined under a microscope. Then all the samples were etched in 2-5% nital solution (5% $HN0_3$ in alcohol) and examined for grain structure.

3.8 SPECIMEN PREPARATION

For the study of the worn edges and in order to formulate tool failure and wear mechanisms, the tools were prepared as below to be examined in a Scanning Electron Microscope (SEM).

Once the tool inserts exceeded any of the criteria stated in Section 3.3 the tools were firstly washed ultrasonically in acetone to remove all dirt and oil stains for at least five minutes. These inserts were then mounted on aluminium stubs with the help of an araldite glue and gold coated before examination in a Scanning Electron Microscope (SEM). The gold coating operation was carried out with an Emscope SC 500 gold coating machine.

Scanning Electron Microscope was an important tool in determining the failure modes and to further understand tool wear mechanisms. Specimens used to study the wear mechanism were prepared by slitting the worn tools with the aid of a diamond slitting wheel. The sectioned tools were then mounted in cold setting resin and hardener. The specimens were ground on silicon carbide paper of 200, 320, 400, 600 and 1200 grit sizes using water as a lubricant. The specimens were polished to 6 and 1 micron finishes using a treatment pad impregnated with respective diamond pastes, an authomet lubricating oil was used during final polishing. Once polished the specimens were washed in ultrasonic bath before coating.

The workpiece specimen was prepared by cutting a small piece from the steel bar. The specimen was mounted and polished as before. The polished specimen was etched with a 2% nital solution (HNO_3 in alcohol). The specimens were then examined and photographed using an optical microscope as shown in Figures 14, 15 and 16.

3.9 CUTTING TOOL MATERIALS

Five types of ceramic tools were used for machining trials (K060, K090, KYON 2500, KYON 2000 and KYON 3000). The ceramic tools used for the machining trials can be grouped into four major categories: the pure oxide ceramics (K090), the mixed oxide ceramics (K090), the SiC whisker reinforced alumina ceramics (KYON 2500) and the sialon ceramics (KYON 2000 and KYON 3000). The latter tools (KYON 2000 and KYON 3000) are generally classified as Si_3N_4 based while the rest are classified as alumina based ceramic tools. Early introduction of ceramic tools to the manufacturing industry was not successful due to the inherent brittleness of the alumina based matrix. The development of production techniques and chemical additions to the base materials have resulted in new ceramic tool materials with improved properties and the ability to machine a wide variety of materials ranging from the 'free machining' materials to the exotic aerospace superalloys (120-121). The toughness of these ceramic tool materials has been improved by chemical modification as well as by mechanical means. Table 3 shows the composition and properties of all the tools used in this project. Figures 17 - 21 shows the microstructures and Figures 22 to 24 shows the TEM images of the ceramic tools used for this project. The properties of these materials as supplied by Kennametal Inc are listed in Table 3.

3.10 WORK MATERIALS

Various grades of steel were used for this work ranging from the plain carbon steel (EN8), alloy steel (EN24) and the hardened steel (D2).

3.10.1 En8 BS970: Part 1: 1970

EN8 is a medium carbon steel widely used for applications where better properties than mild steel are required, but the expense of an alloy steel is not justified. Tensile properties are typically in the range 35/55 p.s.i. A moderate wear resistance can be obtained by flame or induction hardening giving a case hardness of 365-510 HV depending on the carbon content of the steel.

Typical applications are:

Connecting rods, studs, bolts, highly stressed gears, spindles, roller and many vehicle and general engineering components (123).

Chemical Analysis: (123)

	%Min	%Max	Permitted Variation
Carbon	0.36	0.44	+/- 0.03
Manganese	0.60	1.00	+/- 0.04
Silicon	-	-	-
Sulphur	-	0.050	+/- 0.008
Phosphorus	-	0.050	+/- 0.008
Fe	-	Rem	-

3.10.2 EN24 BS970: Part 2: 1970

EN24 is a high quality alloy steel supplied in the hardened and tempered condition to a tensile range of 55/65 t.s.i. This steel exhibits good ductility and shock resistance properties combined with resistance to wear.

The presence of chromium and molybdenum in this steel increases hardenability enabling large sections to be heat treated and permitting slower rates of cooling from the hardening temperature for smaller components, thereby minimising the chance of cracking and distortion. Nickel in steel increases tensile strength and considerably raises the impact resistance. Typical applications include machine parts, gears, pinions, spindles, axles, bolts, studs etc.

Chemical Analysis (123):	%Min	%Max	Permitted Variation
Carbon	0.36	0.44	+/- 0.02
Silicon	0.10	0.35	+/- 0.03
Manganese	0.45	0.70	+/- 0.03
Nickel	1.30	1.70	+/- 0.05
Chromium	1.00	1.40	+/- 0.05
Molybdenum	0.20	0.35	+/- 0.02
Fe	Rem		

3.10.3 D2 Tool Steel: BS4659: Type BD2

D2 tool steel Being of the high carbon, high chromium type, this steel offers very high wear resistance, yet it is tough and machinable. It hardens in air up to large sections with a low order of movement and offers a measure of corrosion resistance when polished.

K.E.A 180 (D2) is used for tools operating under conditions of severe wear and abrasion or as an alternative to oil hardening tool steels when longer runs are required.

Applications include blanking dies and punches for steel and plate, deep drawing dies, cupping dies, forming dies, sheet metal forming rolls, shear blades for strip and sheet including flying shears. Circular cutters for cold rolled strip. Trimmer dies, thread rolling dies, cold extrusion dies. Brick and tile mould liners.

Typical Analysis % :

C	Cr	Mo	V	Fe
1.55	12.0	0.85	0.28	rem

CHAPTER 4

4. EXPERIMENTAL RESULTS

4.1 MACHINING PARAMETERS

The machining experiments were carried out in the absence of a coolant at the following conditions:

Cutting speed (m/min) = 50, 100, 150, 200, 250, 300, 350,400, 450, 500, 550, 600, 650 and 700 m/min

Feed Rate (mm/rev) = 0.16 (mm/rev)

Depth of cut (mm) = 2.00 (mm)

These cutting conditions are typical of those used for roughing, semi-finishing and finish machining operations in the manufacturing industry. Coolants were not used due to two main reasons:

a) Under the above machining conditions, the condition at the interface is that of a seizure and hence coolants may not be able to reach the interface.

b) Tools like ceramics are known to have thermal shock problem and may crack when used in the presence of coolants.

Where required especially coolants may be used when machining steels with ceramic tools in order to keep the work material cool to avoid distortion of the machined components. In such cases the coolant should be directed away from the tool-chip interface.

4.2 MACHINING OF PLAIN CARBON (EN8) STEEL WITH CERAMIC TOOLS

4.2.1 TOOL LIFE AND FAILURE MODES

Tool life is the time it takes for a tool to wear out under the criteria stated in Chapter 3. An accurate record of tool life in a machining test helps to determine the performance of the cutting tool under the specified cutting conditions. A knowledge of tool lives at different cutting conditions will aid in choosing the optimum machining conditions ideal for a given cutting tool material. A study of the failure modes of a cutting tool enables an understanding of the mechanisms of tool wear to be gained. The failure mode is generally controlled by the nature and composition of the work material, the tool material and the cutting conditions.

Figure 25 shows a summary of the tool lives achieved at various cutting speeds when machining the plain carbon (EN8) steel with ceramic tools at a constant feed and depth of cut of 0.16 mm/rev and 2.0 mm respectively. Machining with the KO60, KO90 and KYON 2500 inserts at low speeds of 50 m/min and 100 m/min were aborted after 15 minutes due to the very low wear observed on the tools. It is expected that these grades of ceramics will produce much longer tool lives if machining had continued. The silicon nitride based KYON 2000 and KYON 3000 tools each produced relatively high flank wear rate at low speed conditions giving poor tool lives (Figure 25).

Flank wear was the dominant failure mode when machining the plain carbon steel with all grades of ceramic tools investigated. Fracture of the cutting edge was however, the tool life limiting factor in some cases, especially when machining with the aluminium based (KO60 and KO90) ceramic tools at high cutting speeds (>250 m/min). These tool materials may have been subjected to premature failure by fracture because of their lower fracture toughness relative to the silicon nitride based and SiC whisker reinforced alumina ceramics (Table 3).

From Figure 25 it can be seen that the tool lives generally decreased with increasing cutting speed for most of the tools tested. This was expected as more heat is generated at the cutting edge when machining at higher speeds. This increased temperature tends to combine with the high stresses generated at higher speeds at the cutting edge resulting in rapid tool wear. The pure oxide (KO60) ceramic tools however gave improved performance at high speeds between 400 m/min up to 600 m/min. The KO60 tools failed mainly by fracture under these conditions. The improved performance of the KO60 tools at high speeds could be related to the chemical inertness of the alumina matrix to steel (>99 vol % in KO60).

A comparison of the recorded tool lives show that the pure oxide (KO60) tools gave the best overall performance when machining the plain carbon steel, while the silicon nitride based (KYON 2000 and KYON 3000) tools gave the worst performance. The KYON 3000 insert gave tool lives lower than 3 minutes for all the cutting conditions tested, this was mainly due to accelerated flank wear rate. The KYON 2000 tools also gave poor performance especially at high speed conditions in excess of 300 m/min. KYON 2000 tools however, produced reasonable tool lives at lower speeds up to 250 m/min. In terms of tool lives the mixed oxide KO90 ceramic tools gave the second best performance closely followed by the SiC whisker reinforced alumina ceramics.

4.2.2 FLANK WEAR

Figure 26 shows a plot of the average flank wear versus cutting time when machining plain carbon steel (EN8) with the pure oxide KO60 tools. The curves in Figure 26 generally show rapid flank wear on the tools within the first 5 minutes of machining. The flank wear remained fairly constant after the first 5 minutes. As expected rapid flank wear occurred again towards the end of the cutting period in most tests conducted. Lower flank wear was recorded at low cutting speeds of 50 m/min and 100 m/min (curves 13 and 14 in Figure 26). Increased flank wear rate was observed at higher speeds. Most rapid flank wear rate was recorded at a speed of 300 m/min (curve 9 in Figure 26).

Flank wear readings obtained when machining the plain carbon steel with the mixed oxide (KO90), SiC whisker reinforced alumina ceramic (KYON 2500) and Si_3N_4 based (KYON 2000 and KYON 3000) ceramic tools followed a similar pattern and were generally different from those obtained using the pure oxide ceramics. Figures 27 to 30 show that the flank wear increased linearly with prolonged machining unlike the three stages of wear described earlier for KO60 ceramic tools. Curves 13 and 14 in Figures 27 and 28 did however, exhibited the three main wear regions when machining with the K090 and KYON 2500 tools at low speeds. Figures 27-30 also show that an increase in the cutting speed leads to a proportional increase in the flank wear rate and that the KYON 3000 tools (Figure 30) exhibited the most rapid rate of tool wear under all the cutting conditions.

4.2.3 PURE OXIDE CERAMIC (KO60) TOOLS

On reaching any of the specified tool life criteria, the ceramic tools were cleaned and examined in the scanning electron microscope (SEM) at various magnifications. There was no appreciable wear on the pure oxide, KO60, tools at slow speeds of 50 m/min and 100 m/min after machining the plain carbon (EN8) steel for 15 minutes. The flank faces of the partly used KO60 tools showed even wear with very minute chipping at the cutting edge. Wear on the rake and flank faces of the KO60 tools became pronounced when used for machining at higher cutting speeds. Figure 31 shows a worn KO60 tool used to machine the plain carbon steel at a speed of 600 m/min. Ridges (or grooves) can be seen on the worn rake and flank faces. Figure 31 also shows that a slight crater formed is virtually at the cutting edge of the tool where maximum stresses are generated during machining. Evidence of plucking of tool particles on the rake and flank faces can also be seen on the worn tool. The ridges on the worn flank face became deeper with subsequent increase in cutting speed up to 600 m/min (Figure 32). The bottom of the deep groove in Figure 32 (right) had a plucked appearance. Tiny fragments and/or lumps of tool particles which have been lifted can be seen between the grooves on the worn flank face. Severe grooves on the flank face when machining plain carbon steel at high speed conditions led to a significant deterioration in the surface finish of the machined workpiece. Fracture of the entire cutting edge occurred after 4 minutes when machining plain carbon steel with the KO60 insert at a higher speed of 700 m/min (Figure 33). Any subsequent machining with a fractured tool edge produced very poor surface finish. Crater wear recorded on all the ceramic tools when used for the machining of EN8 was below the tool life limiting criterion of 0.14 mm.

4.2.4 MIXED OXIDE CERAMIC (KO90) TOOLS

The mixed oxide, KO90 tools showed hardly any wear at cutting speeds below 200 m/min after 15 minutes of machining in some cases. Figure 34 shows a general view of the cutting edge of a KO90 tool after machining the plain carbon (EN8) steel at a slow speed of 100 m/min. This figure shows the relatively smooth crater formed very close to the cutting edge as well as grooves on the worn flank face of the tool. There was also significant chipping of tool particles along the entire cutting edge, becoming more severe at the end of the depth of cut region (Figure 35). Evidence of plucking of tool particles was observed between the ridges formed on the worn flank faces of the KO90 tools (Figure 36). This was more pronounced on tools used at speeds in excess of 400 m/min. The KO90 tools generally exhibited a relatively high rate of flank wear/edge chipping than the KO60 tools when machining plain carbon steel, hence compared to KO60 tools lower tool lives were recorded under all cutting conditions with KO90 tools.

4.2.5 SiC WHISKER REINFORCED ALUMINA (KYON 2500) CERAMIC TOOLS

Significant flank wear was observed when machining plain carbon steel with the SiC whisker reinforced, KYON 2500 ceramic tools as shown in Figure 28. At lower cutting speeds up to 100 m/min, the rate of flank wear was less dependent on cutting time. The flank wear increased with prolonged cutting time and also with increased cutting speed. Grooves (or ridges) were observed on the worn flank faces of the KYON 2500 tools under all cutting conditions. These grooves became more severe as the cutting speeds were increased. Premature failure of the KYON 2500 tools by fracture occurred within 2 minutes when cutting at speeds in excess of 550 m/min. Figure 37 shows a severely chipped portion of the cutting edge of a KYON 2500 tool prior to fracture. A magnified view of a chipped section shows cracks, the shearing of tool particles and vacant sites where ceramic particles were lost by the removal of either microscopic size grains or portions of them. The premature failure of the KYON 2500 tools at high speeds may have been caused by such conspicuous cracks observed on the worn flank faces of the tool as shown in Figure 38.

4.2.6 SIALON (KYON 2000 & KYON 3000) CERAMIC TOOLS

Two types of silicon nitride based ceramics, Kennametal's KYON 2000 and KYON 3000 ceramic tools were used in this project. Figures 29 and 30 shows plots of the flank wear against the cutting speeds when machining the EN8 plain carbon steel at various speeds with a constant feed rate and depth of cut of 0.16 mm/rev and 2.00 mm respectively. These figures show a rapid rate of flank wear under all cutting conditions. This phenomenon was more severe when machining with the KYON 3000 tools (Figure 30). Short tool lives recorded with both the KYON 2000 and KYON 3000 tools may be attributed to the accelerated flank wear rate. It is however, interesting to note the absence of fracture on the silicon nitride ceramic tools when machining at high and low speed conditions. This could be due to relatively higher fracture toughness of this grade of ceramics in comparison to the alumina based ceramics (Table 3).

Wear observed on the flank face of the KYON 2000 tools used for cutting at low speeds was generally rough with considerable chipping at the cutting edge. The chipped portion of the cutting edge showed cracks and significant plucking of the worn flank face (Figure 39). The flank faces of the KYON

2000 tools used for machining at high speeds had grooved type appearances. The bottom and crest of the ridges observed at higher speeds had a rough and plucked appearance. Figure 40 shows the bottom of a groove after machining at a speed of 400 m/min where tool particles were lost by the removal of either microscopic size grains or lumps of it. Large cracks were observed on the flank faces of the KYON 2000 tools after cutting the plain carbon steel at higher speed of 700 m/min as shown in Figure 41. Subsequent machining with this severely cracked tool resulted in the eventual fracture of the entire cutting edge.

Wear observed when machining plain carbon steel with the nitride based KYON 3000 ceramic tools was almost similar to that observed with the KYON 2000 tools. The extent of plucking between the ridges on the worn flank faces after machining at high speeds is clearly illustrated in Figure 42. Figure 43 shows the cutting edge of a worn KYON 3000 tool after machining at a speed of 700 m/min. There is clear evidence of chipping at the cutting edge, the irregular wear/grooves on the flank face and a shallow crater on the rake face.

4.2.7 SURFACE ROUGHNESS

The surface finish generated under all cutting conditions was recorded with the aid of a stylus type instrument - Surtronic 3. Figure 44 is a plot of the surface finish generated at the end of each machining trial with the five grades of ceramic tools as used under various cutting conditions. It was not possible to monitor the surface finish at specific intervals in these tests since some of the tools, especially the KYON 2000 and KYON 3000 inserts, gave very short tool lives of less than one minute at high speeds in excess of 400 m/min. The curves in Figure 44 show that high surface roughness values in excess of the rejection criterion (5 um) were exceeded when machining plain carbon steel at low to intermediate speeds of 150 m/min - 350 m/min using the KO60 and KO90 tools. This could be associated with the significant chipping of the KO60 and KO90 tools under these conditions. The chipping of the cutting edge tends to alter the cutting edge geometry thereby increasing the tool-workpiece contact areas. The KYON 2000 tools with relatively short tool lives produced the best surface finishes at the low to intermediate speed ranges (Figure 44). The high surface roughness value recorded with the KYON 2000 tools at a speed of 150 m/min could be due to the existence of a built up edge which effectively increases the tool-chip contact area (Figure 45). The surface roughness curves when machining plain carbon steel with ceramic tools also show that almost similar surfaces were generated at very low speeds of up to 100 m/min. A large scatter in the surface roughness values was observed at the intermediate speed range (between 150 m/min and 350 m/min). This could perhaps be due to the sliding action taking place during chip formation at these cutting conditions. Further increases in cutting speeds beyond 350 m/min produced similar surface finishes due perhaps, to the complete elimination of the sliding action and complete seizure of the tool-chip interface. Nearly all the tools tested produced surface finish below the rejection criterion at high speeds of 400 - 600 m/min. There was a rapid deterioration of the surface finish when machining at very high speeds beyond 600 m/min using the KYON 2500, KYON 2000 and KO90 tools (Figure 44). This may be due to the vibration of the machine tool and the premature fracturing of the KO90 and KYON 2500 tools. Figure 46 shows a plot of the surface roughness values at the point of tool rejection when machining the plain carbon (EN8) steel with various ceramic tools at different speeds using a constant feed rate and depth of cut of 0.16 mm/rev and 2.0 mm respectively.

4.2.8 FORCES GENERATED WHEN MACHINING EN8 STEEL WITH CERAMIC TOOLS

Two component forces, the cutting force (Fz) and feed force (Fx) were recorded at the start of each machining trial. Figures 47 and 48 shows the plots of the recorded component forces at various speeds when cutting plain carbon (EN8) steel with the ceramic tools. The figures show that the cutting force (Fz) is always greater than the feed force (Fx) under all cutting conditions. There was a general reduction in the cutting and feed forces as the cutting speed was increased up to the maximum speed of 700 m/min. The KYON 3000 tools produced the highest forces, especially at low to intermediate speeds up to 350 m/min while the KO90 tools gave the lowest forces under similar conditions. The KYON 2500 tools produced the lowest cutting and feed forces at speeds in excess of 350 m/min. There was a bigger variation in the forces recorded (up to 400N) at lower speed ranges. This variation reduced to between 200 - 300N at higher speed conditions.

4.2.9 TOOL LIFE TESTS

Each machining trial was interrupted at specific intervals in order to check and measure the cutting tools for any of the specified tool life criteria. The ceramic cutting tools used in this project were mainly rejected due to excessive flank wear as well as premature tool failure by fracture and the generation of poor surface finish on the machined workpiece. A Taylor's tool life curve based on the expression VT^n = constant was plotted for each of the tools used as illustrated in Figures 49-53. These curves were linear in most cases as would be expected in Taylor's formula since most of the tools were rejected based on only one thermally activated tool life criterion - the flank wear (4). The different linear lines observed in the plots shown in Figures 49-

53 suggest however, that the tool life may be determined by up to three or more wear mechanisms under the conditions tested.

The optimum cutting conditions when machining plain carbon (EN8) steel with each grade of ceramic tool was obtained by using the tool life line formula (ie. cutting speed x tool life). These calculations revealed that the optimum speeds for machining with the KO60, KO90, KYON 2500, KYON 2000 and KYON 3000 ceramic tools were at 450 m/min, 400 m/min, 250 m/min, 200 m/min and 700 m/min respectively (Figure 49-53).

4.2.10 QUICK STOP TESTS

Quick stop tests were carried out when machining plain carbon steel with ceramic tools at low speeds (up to 100 m/min) in order to study the chip formation. Figure 54 is a quick stop section of plain carbon steel cut at a speed of 100 m/min, a feed rate of 0.16 mm/rev and a depth of cut of 2.00 mm showing the spread of the chip sideways, so that the maximum width is usually greater than the original depth of cut. Figure 54 also shows that the upper surface of the chip is usually rough with pronounced corrugations or steps which develop into periodic cracks leading to eventual segmentation of the continuous type of chips generated. Enlarged sections of the newly formed chip revealed the fracture of the upper surface (Figure 55). These small fragments of the chips tend to accumulate at the tool cutting edge forming a built up edge.

4.3 MACHINING OF ALLOY (EN24) STEEL WITH CERAMIC TOOLS

The cast workpiece bars were subsequently hardened and tempered in order to obtain the required mechanical properties. The hardness and other mechanical properties of the EN24 steel is significantly higher than the plain carbon, EN8 steel. A summary of tool life of the pure oxide (KO60), mixed oxide (KO90), SiC whisker reinforced (KYON 2500) and nitride based (KYON 2000 and KYON 3000) ceramic tools from Kennametal after machining EN24 steel is shown in Figure 56. Flank wear was the predominant cause for rejecting all the ceramic tools tested. Other causes for tool rejection include the generation of poor surface finish on the machined workpiece and tool fracture (especially KYON 3000 inserts) when machining at higher speeds of 450 m/min and above. Other types of failure modes such as notching or severe crater wear were not observed when EN24 steel was machined with different grades of ceramics. It can be seen from Figure 56 that the silicon nitride based KYON 2000 and KYON 3000 inserts gave unsatisfactory performances under all the cutting conditions. These inserts gave tool lives below 2 minutes at low speeds, reducing further to fractions of a minute as the cutting speed increased. Machining with the KO60 inserts at low speeds of up to 200 m/min was stopped after 15 minutes in view of the very low wear at the flank face observed. This was also done in order to stop the work material wastage. All tests below 200 m/min were stoped if there was not a significant wear observed on the tool material.

Figure 56 also shows that the KO90 tools gave the best overall performance when machining at speeds of 350 m/min and above, followed by KO60 tools and KYON 2500. The KO60 tools gave their best performance at speed range of up to 300 m/min. The tool life chart in Figure 56 generally portrays a reduction in tool life with increasing cutting speeds when machining EN24 steel.

4.3.1 FLANK FACE WEAR

This was the major tool life determining factor when machining EN24 steel with different grades of ceramic tools.

Figure 57 shows the flank wear at various speeds when machining EN24 steel with pure oxide, KO60, tools. Relatively slow rate of flank wear at slow to intermediate cutting speeds is clearly demonstrated by curves 7-14 in Figure 57. Here, the flank wear increased gradually with prolonged machining and was generally below the recommended flank wear criterion. Rapid rate of flank wear was obtained as the cutting speed increased from 450 m/min up to 700 m/min. The highest flank wear rate was obtained when machining with the KO60 tool at high speeds of 650 m/min and 700 m/min. Machining at these speeds gave the lowest tool lives of 6 and 5 minutes respectively. The lowest flank wear rate was obtained when cutting at a low speed of 50 m/min. After flank wear was recorded the tools were examined in the SEM. Figure 58 is a section of the worn flank face of a KO60 tool used for cutting EN24 steel at a speed of 100 m/min showing plucked surfaces, flank wear under these conditions was not uniform. Similar plucked appearances were also observed from worn KO60 tools used for cutting at high speeds. Cracks can also be seen penetrating into the tool itself in Figure 59. The cracks on the worn flank face became pronounced after machining at a speed of 700 m/min. Figure 60 shows a portion of the flank face already surrounded by cracks and ready to be dislodged. Such cracks may be initiated by the severe plucking of the tool material in the affected zone.

Figure 61 shows the variation of the average flank wear of the mixed ceramic (KO90) tools over time when machining EN24 steel at various speeds. The curves in this figure shows that comparatively higher flank wear rate was recorded with the KO90 tools. The rate of flank wear seems to be directly proportional to the cutting time under most speeds. Figure 61 (curve 8) also shows that a relatively low rate of flank wear was obtained at a speed of 350 m/min. Machining under these conditions gave an optimum tool life of 25 minutes. Irregular and rough surfaces were observed on worn KO90 tools after machining at slow speeds (Figure 62). The uneven wear on the flank face may be caused by the intermittent contact between the tool and the work material under the BUE conditions (Figure 63). The existence of BUE may result in the deterioration of the surface finish after machining at slow speeds. Significant plucking of tool particles were observed on both the rake and flank faces of the KO90 tools used to machine at slow speeds. At higher magnification, the bottom of a plucked portion revealed the existence of cracks running into the tool flank face (Figure 64). The cracks on the flank face of the KO90 tool were more pronounced at higher cutting speeds of 700 m/min (Figure 65). Chipping of the cutting edge was also observed when machining at higher speeds in excess of 350 m/min (Figure 66). Figure 67 is a close up view of a worn KO90 tool, showing losely bound tool particles ready for plucking between the grooves on the flank face.

Machining of the EN24 steel with the SiC whisker reinforced ceramic (KYON 2500) tools, generally produced shorter tool lives when compared to the KO60 and KO90 tools. Higher flank wear rates were obtained when machining with KYON 2500 tools, as illustrated in the flank wear versus the cutting time curves in Figure 68. The flank wear rate generally increased with increasing cutting speed. Figure 69 is a general view of a worn KYON 2500 tool after machining at a speed of 400 m/min. This figure shows extensive chipping, as well as flaking of the tool at entire cutting edge. Ridges on the worn flank face can clearly be seen in this figure. A close-up view of the worn flank face revealed cracks close to the tool nose and areas where large lumps of tool particles have been plucked off (Figure 70). Cracks were also observed on the worn KYON 2500 tools after machining at slow speeds, as shown in Figure 71. The silicon nitride based ceramic tools (KYON 2000 and KYON 3000) gave poor performance when used for the machining of EN24 steel. It was not possible to plot the flank wear curves due to short tool lives recorded at different conditions. Both the rake and flank faces of the tools were worn badly (Figure 72) in addition to the severe chipping, plucking and cracks which were observed (Figure 72a and 72b).

4.3.2 RAKE FACE WEAR

Very shallow craters were observed in some cases when cutting EN24 steel with the different grades of ceramics. Typical crater wear observed on the ceramic tools is shown in Figure 73. Ridges on the rake face of the tool can be clearly seen in this figure. It was observed that the crater observed was very close to the cutting edge, especially after machining at high speeds.

Chipping and flaking of the cutting edges were observed, Figure 74 is a magnified view of the worn rake face of a KO90 tool after cutting at a slow speed of 100 m/min. This figure shows the extent of plucking on the rake face at low speeds. Plucking can be described as the disloging of individual particles from the matrix of the tool by localised stress concentration during machining. Severe plucking observed on the tool rake face may lead to the initiation of cracks. The plucked tool particles may be sandwiched between the tool rake face and the fast flowing chips, on which they get embedded when it moves over the rake face. This severe plucking action may be accelerated by increased temperature generated when machining at high cutting speeds as a result of a combination of high temperatures and high fluctuating streses at the cutting edge.

4.3.3 SURFACE ROUGHNESS

The generation of poor surface finish when machining EN24 was another criteria for tool rejection. An attempt was made to investigate the effect of cutting speed and cutting time on the surface finish generated. This investigation was hindered to some extent by the relatively short tool lives of some of the ceramic tools, especially the silicon nitride based KYON 2000 and KYON 3000 inserts. Figure 75 shows the recorded surface roughness values at the point of tool rejection when machining with the ceramic tools. Some of the tools used produced high surface roughness values beyond the rejection criterion, especially those used at high speeds of 400 m/min and above. Figure 75 also shows that there was no significant difference in the surface finish generated when machining with most ceramic tools at slow to intermediate speed ranges up to 350 m/min. Significant variation in surface roughness was recorded when machining with different tools at speeds in excess of 350 m/min. It will also be noted that shorter tool lives were recorded at higher speeds. A rapid deterioration of surface finish under these conditions could be associated with the severe chipping or flaking of the cutting edges.

The curves in Figure 76 show that the highest surface roughness values were recorded when machining with KYON 2000 and KYON 3000 inserts while the lowest values were recorded with KO90 and KYON 2500 tools. In order to properly investigate the effect of cutting speed on the surface finish generated at different speeds conditions, surface roughness values were recorded after machining for 15 seconds with each grade of ceramic tools (Figure 98).

4.3.4 COMPONENT FORCES

The component forces recorded under various cutting speeds when machining EN24 steel with the five grades of ceramic tools are shown in Figures 77(a) and(b). These forces were recorded with a fresh edge at the begining of each cut. Both the component forces first increased as the speed was raised from 50 m/min to 150 m/min, followed by a gradual drop up to a speed of 550 m/min. A further increase in the cutting speed produced a slight increase in the component forces. The KYON 2500 tools produced the highest cutting forces when machining at the speed range (between 150 to 350 m/min) and the lowest cutting and feed forces at higher speeds. KYON 3000 tools produced the highest cutting and feed forces at the high speed conditions. It can be seen from Figure 77 (a and b) that component forces generated with both the KO60 and KO90 tools are almost similar, and were usually small at most cutting speeds.

4.3.5 TOOL LIFE COMPARISON

The comparison of the performance of the different ceramic tools used to machine EN24 steel is shown in Figure 56. Optimum cutting speed for each tool grade, using the tool-life line formula was found to be within the speed range between 200 m/min and 350 m/min. These optimum speeds are 200 m/min for the KYON 2000 tools, 250 m/min for both the KO60 and KYON 3000 tools, 300 m/min for the KYON 2500 and 350 m/min for the KO90 tools.

4.4 MACHINING OF HARDENED (D2) STEEL WITH CERAMIC TOOLS

This medium alloy and high carbon-chromium air hardening tool steels grouped under AISI A and D series encompass possibly the most useful selection of tool steels available to engineers today. The steel in this group show high wear resistance, good depth hardening properties and, with properly balanced alloy additions, give low dimensional change in hardening. In the medium alloy steels, manganese, chromium, molybdenum and vanadium are the principal alloying elements. Main function of alloy additions is to promote depth hardening, thus minimising distortion and of course, the high carbon coupled with chromium and molybdenum ensure high wear resistance.

In the D series, the principal alloying elements are chromium and carbon. In certain cases, additions of tungsten, molybdenum, cobalt and vanadium are also there. The steels in this group show extremely high wear resistance, good deep hardening properties and with properly balanced alloy additions, give extremely low dimensional change on hardening.

4.4.1 FAILURE MODES

Flank wear was the major cause of tool rejection when machining D2 steel with the five grades of ceramic tools investigated in this project. The generation of poor surface finish on the workpiece material contributed to tool rejection mainly when machining with KO60 and KO90 tools at higher cutting speeds of 400 m/min and above.

Figure 78 is a summary of tool lives of pure oxide (KO60), mixed oxide (KO90), whisker reinforced (KYON 2500) and nitride based (KYON 2000 and

KYON 3000) ceramic tools used for cutting D2 steel. Machining with the pure oxide, mixed oxide and whisker reinforced ceramic tools at lower speeds, up to 200 m/min, was stopped after 15 minutes due to very low flank wear recorded. The nitride based KYON 2000 and KYON 3000 inserts gave very poor performance under these conditions, as well as for all the cutting speeds tested. Both the KYON 2000 and KYON 3000 tools gave tool lives below 2 minutes when machining at lower speeds, decreasing to less than one minute as the cutting speed was increased. A tool life of 25 minutes was obtained when cutting with the KO60 tool at a speed of 250 m/min. Longer tool lives of 30 and 35 minutes were obtained when machining with the KO60 inserts, at speeds of 300 m/min and 350 m/min respectively. Subsequent increases in cutting speeds resulted in a gradual reduction in tool life, with the rise in cutting speed shorter tool life was also recorded with KO90 and KYON 2500 tools. Slight cratering was observed on the worn ceramic tools after machining the D2 steel with ceramic tools. Other failure modes such as notching or tool fracture were not observed when machining D2 steel with any of the five grades of ceramic tools used in this project.

4.4.2 FLANK WEAR

The effect of cutting time on the average flank wear when machining D2 steel with KO60 inserts is shown in Figure 79. The curves in this figure show that the average flank wear criterion did not feature prominently in the tool rejection when cutting with KO60 tools since they were all below the rejection criterion of 0.40 mm. There was however a rapid increase in the maximum flank wear recorded and most were in excess of the established criterion of 0.60 mm maximum flank wear as illustrated in Figure 80. KO60 inserts were prone to fracture at the cutting edges when machining D2 tool steel due perhaps, to their inadequate fracture toughness relative to other grades tested. Figure 81 shows the extent of flaking at the cutting edge of a KO60 insert after cutting at a low speed of 100 m/min. A deep crack running from the tool nose to the flank face as well as lumps of tool particles already undermined can be seen. Extensive plucking on the irregularly worn flank face can also be seen in Figure 82. The flaking at the insert edges was more severe when machining at speeds of 500 m/min and above resulting, in poor tool life. Higher rate of edge flaking could also be due to the vibration which was generated on the machine when operated at such high speeds. Figure 83 is the cutting edge of a worn KO60 insert after machining at a high speed of 700 m/min, showing chipping at the cutting edge near the nose and minimum wear at the rake and flank faces.

The effect of cutting time on the average flank wear when machining D2 steel with the KO90 inserts, is shown in Figure 84. The relatively low flank wear rate at lower speeds up to 200 m/min is clearly illustrated with curves 11-14 in Figure 84. An increase in the flank wear rate occurred as the cutting speed was raised beyond 200 m/min. Figure 85 is a section of the worn rake and flank faces of the KO90 tool after machining at a speed of 400 m/min. The extent of wear on both faces can be clearly seen as well as the plucking on the worn faces. A rapid rise in the flank wear rate occurred at higher cutting speeds of 650 m/min and 700 m/min.

Three distinct flank wear rates were observed after machining with the KYON 2500 inserts at various speeds (Figure 86). Machining at the lower speeds up to 200 m/min gave the lowest flank wear rate, followed by a slightly higher flank wear rate at intermediate speeds between 250 m/min and 350 m/min, and the rapid flank wear rate at high speed conditions above 350 m/min. Very little chipping occurred at the edges of the KYON 2500 inserts after machining at lower cutting speeds (Figure 87), this may be due to the increased fracture toughness of the SiC whisker reinforced alumina ceramic tool relative to other grades of ceramic tools tested. Pronounced ridges were however, observed on the worn flank face of the insert after machining at lower speeds as can be seen in Figure 87. A close-up view of the ridges showed had a sort of plucked appearance (Figure 88). Severe and rough wear was observed on the flank faces of the KYON 2500 insert after machining at an intermediate speed range as shown in Figure 89. This figure shows a combination of flaking at the cutting edge, plucking and cracks on the worn flank face. A close-up view of the severely worn flank face highlighting these failure modes is shown in Figure 90. Extensive damage occurred on the flank face of the KYON 2500 inserts after machining at high speed conditions. Figure 91 is a section of the worn flank face of the KYON 2500 insert showing wear of the tool particles. A magnified view of the badly worn flank face reveals the extent of the dislodging of the tool particles on the flank face, below the primary cutting edge (Figure 92). Such phenomena was found to accelerate flank wear rate at high speed conditions (Figure 86) resulting in the premature fracture of the entire cutting edge with further machining.

It was not possible to produce plots of the flank wear versus cutting time after machining with the silicon nitride based KYON 2000 and KYON 3000 inserts due to very short tool life at various cutting conditions investigated. Both grades of ceramics exhibited similar wear patterns at different speeds. Ridges were observed on the worn flank faces after machining at lower speed conditions (Figure 93). The bottom of these ridges had a plucked appearance. Figure 94 shows the cutting edge of a KYON 3000 insert after machining D2 steel at a speed of 400 m/min. Erosion of tool materials at the primary cutting edge, crater wear and flank wear can be clearly seen in this figure. A view of the crater observed (Figure 95) shows extensive plucking of tool particles. The plucked tool particles may be carried away at the undersize of the fast flowing chip and deposited at the end of the chip-tool interface on the tool rake face. Cracks were observed on the worn flank face of the KYON 3000 tool, as well as the removal of layers of tool particles (Figure 96). The removed layers of tool material may have been sandwiched between the tool workpiece interface resulting in subsequent enhanced flank face wear. Erosion of tool particles at the cutting edge of the KYON 3000 tool became more severe when cutting at a higher speed of 700 m/min (Figure 97). This led to a complete distruction of the tool edge geometry, with an adverse effect on surface finish and overall tool performance.

4.4.3 SURFACE ROUGHNESS

Surface finish was the dominant cause for tool rejection when machining D2 steel with the KO60 and KO90 tools at speeds between 450 m/min and 550 m/min. These tools produced high surface roughness values at the later stages of the machining operation due perhaps to high flank wear (maximum wear for KO60 tools) recorded which could alter the cutting edge geometry. Realistic evaluation of the surface finish generated with each grade of ceramic insert tested was only carried out by recording surface roughness values at the beginning of each test at high speed conditions since the KYON 2000 and KYON 3000 inserts gave very short tool lives. Figure 98 shows the surface roughness values recorded at the start of cut when machining D2 steel with five grades of ceramic tools tested. Low surface roughness values were recorded in most cases as would be expected at the beginning of the cut. Relatively high surface roughness value recorded with the silicon nitride based KYON 3000 and KYON 2000 inserts at high speeds could be associated with the early appearance of chipped surfaces at the cutting edges. similar surface roughness values were recorded with other grades of ceramic tools tested. The curves in Figure 98 show a slight reduction in the surface roughness values as the cutting speed was increased from 400 m/min to 550 m/min. Further increase in cutting speeds resulted in a slight deterioration in the initial surface finish when machining D2 steel. There was also a general deterioration of the surface finish with prolonged cutting time.

4.4.4 COMPONENT FORCES

The component forces recorded under various cutting conditions when machining D2 steel with ceramic tools are shown in Figure 99 (a and b). The pattern of the curves for both the cutting (Fz) and feed forces (Fx) were similar, showing a general reduction in component forces as the cutting speed increased. The cutting force was always greater than the feed force. Figure 99 shows an increase in the cutting force when machining with KYON 3000 insert at a speed of 100 m/min. Subsequent increases in cutting speed produced lower cutting forces. Figure 99 (a and b) shows that the highest cutting and feed forces were recorded when cutting with KYON 3000 inserts. Machining with KO60 inserts gave the lowest feed forces under all the cutting conditions. KYON 2500 inserts gave the lowest cutting forces at lower speeds up to 350 m/min while KO60 and KO90 inserts produced the lowest cutting forces at speeds in excess of 350 m/min.

4.4.5 TOOL LIFE TESTS

Detailed tool life tests were carried out under all the stated cutting conditions. The cutting tools were examined for their useful life at specific intervals, or when severe damage occured at the cutting edge. It can be seen from Figure 78 that the KO60 inserts gave the best performance and the wear rates were low. This can be attributed to the higher alumina content in the composition. Increased alumina content may tend to retard thermally related wear mechanisms which are dominant at high speed conditions where higher temperatures are generated during machining operation. The optimum cutting conditions for all the grades of ceramic tools tested falls within the intermediate speed range. The KO60 tools can be most economical when machining at a speed of 400 m/min while the KO90, KYON 2500 and KYON 2000 tools are most economical when cutting D2 steel at a speed of 300 m/min. Optimum machining speed for the KYON 3000 inserts was achieved at a lower speed of 250 m/min.

4.5 COMPARATIVE TOOL LIFE TESTS

The tool life data plotted in Figures 100-104, compares the performance of each of the five grades of ceramics when machining EN8, EN24 and D2 steels. In all cases, the tools were rejected after they reached or exceeded any of the tool life criteria as stated in chapter 3.

Most of the machining tests with KO60 inserts at low speed conditions (up to 200 m/min) were stopped after 15 minutes, due to the relatively low tool wear observed. Flank wear was the predominant cause for tool rejection when machining the three grades of steel with the pure oxide, KO60 ceramic tools. Figure 100 shows that the shortest tool lives were obtained when machining EN8 steel at the intermediate speed conditions between 250 m/min-350 m/min. EN24 steel only gave the longest tool life when machining with KO60 tools at a speed of 250 m/min. Figure 100 also shows that the longest tool lives were recorded when machining D2 steel with KO60 at speeds above 250 m/min, while machining EN24 steel under similar conditions gave the shortest tool lives. Machining EN8 steels with KO60 at high speeds of 450 m/min and 500 m/min gave the longest tool lives of 25 minutes and 10.15

minutes respectively. General decline in the recorded tool life with increasing speed above 300 m/min, is clearly illustrated in the tool life data plotted in Figure 100.

Figure 101 is the tool life data plotted when machining different grades of steel with the mixed oxide, KO90, ceramic inserts. Low tool wear was recorded when machining D2 steel with KO90 inserts, up to speed of 200 m/min, hence further machining was stopped after 15 minutes. Further machining was also stopped after 15 minutes for the same reason when cutting EN8 steel at low speeds of 50 m/min and 100 m/min. Significant wear was recorded when machining EN24 steel with KO90 inserts at low speeds up to 200 m/min. Generations of poor surface finish on the machined surface was the cause of tool rejection when machining EN24 steel at a very low speed of 50 m/min. It can be seen from Figure 101 that the longest tool lives were recorded when machining D2 tool steel at the intermediate/high speed ranges, between 250 m/min and 450 m/min, and when machining EN24 steel at higher speeds between 500 m/min and 700 m/min. The shortest tool lives were recorded when machining EN8 steels with the KO90 tools under most of the cutting conditions tested.

Figure 102 is a plot of the tool life data when machining three grades of steel with SiC whisker reinforced, KYON 2500, ceramic inserts. In nearly all cases, especially at speeds beyond 200 m/min, KYON 2500 inserts were discarded after they exceeded the specified wear on the flank face or due to the generation of poor surface finish on the machined surfaces. Machining with KYON 2500 inserts at low speeds (below 200 m/min) usually gave very low tool wear rate. There was a significant increase in the rate of tool wear as the cutting speed increased beyond 200 m/min. Rapid rate of flank wear occurred at high speeds in excess of 500 m/min. It can also be seen from

Figure 102 that the best overall performance of KYON 2500 inserts was achieved when machining
medium carbon (EN8) steel while machining of EN24 steel gave the worst performance. Optimum performance of the SiC whisker reinforced, KYON 2500, ceramic tools was obtained when machining medium carbon steel (EN8) at cutting speeds of 250 m/min and 300 m/min.

Relatively low tool lives were recorded when machining three grades of steel with the silicon nitride based KYON 2000, ceramic inserts at all the cutting speeds tested (Figure 103). Short tool lives obtained due to the high rate of wear on KYON 2000 tools. It is however, interesting to note that wear on the flank face was the major cause of tool rejection, and none of the KYON 2000 tools fractured during all the machining trials as was observed with all other ceramic tools. Figure 103 shows that the longest tool lives were obtained when machining EN8 steel with KYON 2000 inserts under slow and high speed conditions. Much lower tool lives were recorded when machining both EN24 and D2 steels with KYON 2000 inserts at all cutting conditions tested in this project. The tool life data chart shows a significant drop in the performance of the KYON 2000 inserts when machining three grades of steels at higher speeds. It is evident from the tool life data in Figure 104, that the longest tool lives were also recorded when machining EN8 steel with KYON 3000 inserts at all cutting speeds tested. Machining D2 steel gave the shortest tool lives at low speeds up to 200 m/min, while cutting the EN24 steels gave the shortest tool lives at higher speeds.

A comparison of Figures 103 and 104 shows that much shorter tool lives were recorded when machining with the KYON 3000 tools, due to excessive wear which may have resulted in the fracture of the entire cutting edge when machining the EN24 steel at high speeds above 450 m/min. The tool life data in Figures 100-104 also show that KO60 inserts gave the best overall performance when cutting three grades of steel at various cutting conditions. The ranking of other grades of ceramics tested in terms of performance are KO90, KYON 2500, KYON 2000 and KYON 3000.

4.6 COMPARISONS BETWEEN CERAMIC AND CEMENTED CARBIDE TOOLS

In order to compare the behaviour of ceramic and cemented carbide tools, limited machining trials were carried out using two different kinds of carbide inserts (coated and uncoated). The speed at which these comparison tests were carried out were chosen from the manufacturers recommendations. The cemented carbide tools used were produced by Sandvik Coromant and conform to ISO specification S6P40 (uncoated) and 425P25 (triple coated). These inserts were tested at cutting speeds of 250 and 400 m/min respectively.

Figure 105 and 106 shows the recorded tool lives when machining the different steel work materials with the ceramic and uncoated carbide (S6P40) and coated carbide (425 P25) inserts, at a speed of 250 and 400 m/min respectively; a feed rate of 0.16 mm/rev and a depth of cut of 2mm. Both figures generally show similar patterns in terms of recorded tool lives. The longest tool lives were always recorded when machining with the pure oxide (K060) at both cutting conditions tested. The next best tool was the mixed oxide (K090) ceramics, followed by the silicon carbide whisker reinforced alumina (KYON 2500) ceramics. Both the uncoated and coated cemented carbide inserts out-performed the silicon nitride based ceramic (KYON 2000 and KYON 3000) tools at speeds of 250 m/min and 400 m/min respectively. In general, the alumina based ceramic tools gave longer tool lives when machining various types of steel, due to the very high resistance of the alumina major constituent to solution wear. The tungsten carbide in both the coated and uncoated carbide inserts has higher solution wear rate than the alumina ceramics, hence they generally exhibit high tool wear rate. The very poor performance of KYON 2000 and KYON 3000 inserts was mainly due to a poor resistance of the silicon nitride based material to solution wear relative to the alumina and cemented carbide tools. There is a tendency for an uncontrolled diffusion of iron from the work materials into the cutting tool resulting in a high tool wear rate hence shorter tool lives.

Table 3 shows different composition of the ceramic tools used and the percentages of alumina contained in pure oxide, mixed oxide and silicon carbide whisker reinforced alumina ceramic tools. As it can be seen from Table 3, as the percentage of alumina reduces, so the tool becomes prone to solution wear resulting in high tool wear rate, hence short tool life.

CHAPTER 5

5.0 DISCUSSION

5.1 INTRODUCTION

This project involved detailed machining trials of three grades of steel (EN8, EN24 and D2 TOOL STEEL) using five different grades of ceramic tools (KO60, KO90, KYON 2000, KYON 2500 and KYON 3000) with the aim of achieving a better understanding of the behaviour of ceramic tools when machining these work materials. Published works in this field have so far, concentrated on the investigation of specific aspects of the individual tool/workpiece combination, and sometimes studies on the failure modes and wear mechanisms of ceramic tool materials have been carried out using practical and theoretical approaches. This work will provide a comprehensive guide to the economic machining of steels with ceramic tools, both from the practical and theoretical stand points. It will also identify the strengths and weaknesses of available ceramic tool materials at various cutting conditions investigated during this project.

The objective of this project was to generate machinability data and to investigate the failure modes and wear mechanisms of ceramic tools when machining various grades of steel. Detailed machining tests were performed with each grade of cutting tool at various cutting conditions in order to formulate optimum machining conditions.

Failure mode and wear mechanisms were studied from three stand points:

(i) The effect of the tool material

(ii) The effect of the workpiece material

(iii) The effect of cutting speed

5.2 WEAR FEATURES OF CERAMIC TOOLS

Cutting edges of the ceramic tools were examined after every two to four minutes machining of interval, in order to record tool wear rates. Once the tool reached its tool life criteria, they were examined under the optical and SEM to study the tool failure modes and wear mechanisms.

Typical wear features observed after machining steels with ceramic tools under various cutting conditions were:

(i)	Plucked areas	eg. Figure 67
(ii)	Ridged areas	eg. Figure 87
(iii)	Smooth and shinny areas	eg. Figure 34
(iv)	Chipped and flaked areas	eg. Figure 69
(v)	Cracked areas	eg. Figure 60
(vi)	Irregularly/roughly worn areas	eg. Figure 89
(vii)	Fractured areas	eg. Figure 33

Contrary to expectation, only minor notching was observed Figure 83. Notch formation (mainly at the depth of cut region and tool nose) in cutting tools has been attributed to both mechanical (124) and chemical (125) wear mechanisms. The mechanical cause for notching can be associated with the machining of work hardened materials. The chemical cause for notching is predominant at high speed conditions which encourages inter-atomic diffusion of various elements (particularly iron), from the work materials to the tool materials and vice versa. This action usually takes place at the tool nose and end of the depth of cut regions as a result of the sliding action which encourages the access of gases (especially oxygen) from the atmosphere into the tool-chip and tool-workpiece interfaces thus accelerating wear at these regions. Only minor presence of notching when machining the different grades of steels with ceramic tools could be due to the chemical inertness of ceramic tools at elevated temperatures as well as their ability to maintain high hardness and strength levels at the high speed condition.

Pronounced ridges were observed on both the rake and flank faces of ceramic tools used to machine the steel work materials. The width of the ridges formed increased with the increase in cutting speed or with increasing temperatures. A similar observation has been reported by Brandt (126) when machining steel and Ezugwu (86) when machining grey cast iron with ceramic tools. The ridges observed normally, had a fairly smooth appearance (Figure 87) and some were rough (Figure 32). In both cases, the grooves formed had plucked appearances as well as traces of adhered workpiece material on the flank face. The adhered work material was removed by etching in dilute hydrochloric acid before the worn tools were observed on the Scanning Electron Microscope (SEM). A probable cause of the ridges observed on the ceramic tools are plucked off tool particles which were sandwiched between the chip-tool or tool-workpiece interfaces and subsequently, scratching the rake and flank faces as they are dragged along the worn surfaces (127). Figures 67 and 81 show lumps of dislodged tool particles which tend to travel down the tool flank face via already created grooves, thus widening them and causing rapid tool wear during machining. The growth of the cracks at the cutting edge can be accelerated during machining operation as a result of the vibration of the machine tool and/the cutting tool particularly at high speed conditions. This could lead to the subsequent failure of the entire cutting edge if machining is not halted.

Plucking of the tool particles was observed at the entire cutting edges (particularly on the flank faces) when machining at various speeds (Figure 88). Plucking can be described as the dislodging of individual particles from the matrix of the tool by localised stress concentration during machining operation as shown in Figure 67. An increase in cutting speed will result in higher temperatures which may encourage the development of an uneven stress region on the cutting tool, subsequently lowering the cohesive strength of the ceramic bond. This action will result in the plucking of minute particles or large lumps from the cutting edge of the tool.

The plucking of tool particles is largely linked with the attrition wear mechanism which usually occurs at slow speeds when there is intermittent adhesion between the workpiece and the cutting tool. When seizure between the workpiece and the cutting tool is broken, small fragments of the tool can be plucked out and carried away on the underside of the chip or by the workpiece. This usually takes place at low cutting speeds and feed rates (sliding conditions) and if a partially unstable BUE is present. The random tearing away of the BUE can pluck out tool material and move along the freshly machined surface or the underside of the chip. Attrition wear is further aggravated by lack of rigidity of the machine tool and tooling system encouraged by vibration induced chatter.

Adverse effects of the formation of ridges on worn ceramic tools are the deterioration of the surface finish of the machined component, as well as the initiation of thermal cracks which usually nucleate immediately after the tool was disengaged from the workpiece by tensile surface stresses generated during cooling. The formation of ridges at the tool edge will restrict complete tool-chip and tool-workpiece contact thus permitting access of debris from either the work material or the cutting tool at these interfaces. This may lead to the partial or complete welding of the debris onto the rake and flank faces resulting in the formation of BUE and giving a blunt cutting edge even at high speed conditions. The dynamic nature of the welded debris may further accelerate tool wear by the severe alteration of the cutting edge geometry.

Smoothly worn areas were mainly observed on the rake faces of the ceramic tools used for the machining of the steel work materials (Figure 34). The smooth areas were observed within the slight crater formed after the machining of steels with ceramic tools. As was expected the steel work materials are ductile and usually produce long continuous chips during machining. Crater formation is usually associated with thermally related wear mechanisms (mainly diffusion wear) during machining. This type of wear mechanism is predominant when machining at high speed conditions where elevated temperatures are generated at the tool edges. Since only slight crater wear was observed on the worn ceramic tools, any scratches produced are probably active sites for diffusion. This will be sheared along the small crater formed with prolonged machining and will become invisible under the microscope. It is expected that more scratching will take place on the flank face of the cutting tools since the conditions there are almost pure shear. The solubility of silicon and nitrogen (from the silicon nitride based ceramics) in iron, usually causes a severe crater when machining metals (especially steel) which form long continuous chips across the rake face of the tool. North (128) has reported that sialon type ceramics (KYON 2000 and KYON 3000) with relatively low room temperature hardness, will retain their hardness much better than the pure oxide (KO60) and mixed oxide (KO90) ceramic tools so that above 400 degrees centigrade, they are the hardest of the three grades of ceramic tools. This is why sialon tools are recommended for high speed machining where high temperatures are expected. Alumina based ceramics usually have low thermal conductivity (Table 3). The addition of TiC (for KO90) and SiC (for KYON 2500) raises both their thermal conductivity and hardness thus lowering the cutting edge temperature by about 75 degrees Centigrade (129). This lowers the rate of diffusion at the tool-chip interface, resulting in minimum crater.

The conditions for the formation of smooth areas show that they occur where there is "complete seizure" between the tool and the chip during machining. The absence of smooth areas on the flank face of the tools may be due to the deformation of the tool material near the cutting edge, as a result of the shift of the heated zone closer to the cutting edge (common at the high speed conditions) (43). This weakens the cutting edge and causes the elimination of the clearance angle thereby establishing complete contact between the tool and the work material down the flank, forming a new heat source. This additional heat source combines with the heat from both the rake and flank faces of the tool, causing rapid tool wear which can be sudden and catastrophic with further machining. The formation of microchips on the flank face of the tool can also lead to the absence of smooth areas. A microchip is the counter part of the BUE which normally forms on the flank face of a tool. Microchips occur through a process of shear with the development of a primary deformation zone similar to that normally associated with chip production at the tool rake face. The microchips formed on the flank face may hinder the perfect tool-workpiece contact and can also distort the overall appearance of the flank face to produce rough surfaces on the tool flank face.

Extensive chipping/flaking occurred mainly at the cutting edges and also on the rake and/or flank faces of the tools used for machining at high and low speed conditions (Figures 33, 37, 66 and 69). This in addition to severe flank wear and gross fracture of the entire cutting edge are the typical failure modes of ceramic tools. Ceramic cutting tools are generally prone to severe chipping during machining operations (especially intermittent cutting) due to their poor thermal/mechanical shock resistance and inadequate fracture toughness relative to cemented carbide cutting tools. The catastrophic failure (or fracture) of ceramic tools used to machine steel work materials can also be attributed to the additional heat source as a result of the deformation of the cutting edges and the subsequent elimination of clearance angle when machining at high speed cutting conditions. Plastic flow of the tool tip usually occurs when the temperature at the cutting edge is too high relative to the softening point of the tool material. When plastic flow occurs at the tool tip, tool clearance is lost causing a sudden rise and a rather rapid failure of the tool. Excessive chipping and eventual fracture of the cutting tools can also be caused by improper cutting conditions, chatter and poor tool design. This is why extremely rigid machine tools and proper support (or clamping) of the machined part are necessary when machining with ceramic tools.

Cracks were observed on the ceramic tools used for cutting at speeds above 300 m/min (Figures 60, 65, 70 and 96). Cracks also occured on some tools used for machining EN24 and D2 tool steels at lower speeds (Figures 64 and 81). The appearance of cracks mainly at high speed conditions show that they are temperature dependent. Pekelharing (130) reported that thermal cracking does not take place until certain values of speed and feed are exceeded or before a minimum temperature is reached during the cutting period. Cutting speed has a greater influence on tool temperatures than feed rate, thus machining at high speeds results in higher edge temperatures. An increase in the feed rate increases the length of contact between the chip and tool, with an extension of the heated area further from the cutting edge and deeper below the rake face. Dearnley and Trent (131) reported temperatures as high as 1100 degrees Centigrade at the crater when machining steel with cemented carbide tools. Ceramic tools have a lower thermal conductivity than cemented carbides, thus their edge temperatures are expected to be higher (up to 1600 degrees Centigrade) (132). Thermal cracking during cutting operation is expected to take place during the cooling part of the cycle when tensile stresses are developed on the surface of the tool. The absence of cracks on worn KYON 2000 and KYON 3000 inserts after machining steel workpieces could be attributed to the low thermal expansion coefficient of the silicon nitride based ceramics (see Table 3), coupled with their high strain to failure. This reduces the stresses set up between the hotter and cooler parts of an insert thus providing excellent thermal resistance. These characteristics are particularly relevant to interrupted cutting or heavy feed situations, and where materials develop a lot of heat on deformation through work hardening. Machining at high cutting speed also results in shorter chip tool contact lengths. This is disadvantageous since a relatively smaller area will be heated up during machining thus weakening the tool edge. The cracks observed may have been caused by high uneven mechanical stresses compounded by high temperatures and thermal stresses at the cutting edge.

Tool fracture occurred mainly when machining with the pure oxide (KO60) and mixed oxide (KO90) ceramic tools at speeds above 250 m/min. This may be associated with the lower fracture toughness of the pure and mixed oxide ceramics relative to the SiC whisker reinforced alumina (KYON 2500) and silicon nitride ceramic tools (Table 3). The absence of fracture when cutting at lower speeds is due to the increased chip-tool contact length/contact area as a result of the "sliding" of the chip up the rake face when a cut is applied. This produces a reduction in the shear angle with an increase in chip thickness as well as an increase in the shear strain in the chip until the shear strain fracture is reached (133). The distribution of stresses when cutting at lower speeds takes place over a relatively large area of contact, thus avoiding unusual stress concentration at the cutting edge. An increase in the length of chip-tool contact length/contact area when machining cast iron with ceramic tools at lower speeds have been previously reported (86). It is expected that similar observation will be obtained when machining steels at the same cutting conditions. Lower temperatures generated at low speed conditions also helps to prevent stress concentration at the cutting edge thereby ensuring continuous cutting of the tools without fracturing. It was not possible to classify the broken inserts with respect to fracture mode since the initial fracture surface was often destroyed prior to stopping the lathe. Brandt (126) identified three distinct fracture modes when cutting with ceramics as those through a notch at the tool nose, those through the flank wear and those through the rake face, parallel with the flank face. Fracture occurs when the temperatures generated during machining are sufficiently high to allow the stresses acting on the tool to exceed the intergranular bond strength (134). It would have been ideal for the KYON 2000 and KYON 3000 tools to fracture easily during machining as a result of the very rapid wear rate and extremely short tool lives obtained. The absence of fracture when machining with the silicon nitride based ceramics is obviously due to their very low coefficient of thermal expansion as previously discussed.

5.3 EFFECT OF CUTTING SPEEDS ON TOOL WEAR

Various grades of steel were machined with various grades of ceramic tools at different cutting speeds while maintaining a constant feed rate and depth of cut of 0.16 mm/rev and 2.0 mm respectively. The use of high cutting speeds in metal cutting is known to result in rapid tool wear (up to three fold increase in some cases). Similar increases in feed rates equally produce high tool wear rate and failure due to deformation as well as a deterioration in the surface finish generated during machining. An increase in the depth of cut does not effect rapid tool wear during machining when compared to proportional increases in cutting speed and feed rate. The use of high and uneven depth of cut during machining can, however result in the fracture of part of the cutting edge not engaged in cutting due to the impact by the swarf curling back onto the edge or entangling the tool (41).

Most of the ceramic tools tested, except for KYON 2000 and KYON 3000 tools, gave minimum wear when machining at low speeds up to 200 m/min. Tool wear in general, increased significantly with increasing cutting speed up to 700 m/min. Cutting tools used at low speeds were more often rejected by mechanical wear, typically attrition (Figure 110) while those used for machining at intermediate and high speeds were often terminated by thermally dependent wear mechanisms eg. diffusion wear (Figure 111), plastic deformation (Figure 112) and/or fracture (Figure 113) in addition to mechanical wear. Abrasion wear takes place by the mechanical action of hard carbides, oxides and nitrides present in the steels. Low tool lives obtained with both the KYON 2000 and KYON 3000 tools when machining three grades of steel especially at higher speeds was due to poor resistance of the silicon nitride base tool material to solution wear relative to the alumina base ceramic tools. There seems to be an uncontrolled diffusion of iron (Fe) from the work material into the cutting tool resulting in high tool wear rates observed. Relatively smooth and reflective wear observed on a sectioned silicon nitride based ceramic tool (Figure 111) after machining steel are indications of diffusion wear process. Similar wear processes have been reported by Jawaid (7) and Ezugwu (86) when machining ferrous work materials. Structure of the silicon nitride based ceramics consists of the Si_3N_4 cemented by a glass phase. It was thought that iron from the work materials was diffusing into the glass matrix of silicon nitride based ceramics. The diffusion of iron into the glass has been reported by Kieffer (134). Elements like iron are refered to as modifiers and on diffusion they usually change the flow properties of the glass by reducing its viscosity thus lowering its melting temperatures. The diffusion of iron from steel work materials into Kyon 2000 and Kyon 3000 tools was believed to be performing a similar function, diffusing into the secondary phase and acting as a modifier. Thus reducing the viscosity of the glass phase and enhancing its flow. Plucking of the Si_3N_4 grains or lumps of it will be easier as a result of the reduction in the viscosity of the glass phase. This may have resulted in an increased tool wear rate observed when cutting with the Kyon 2000 and Kyon 3000 inserts. Al_2O_3 based tools however behaved differently and gave a good tool life under such conditions, this can be atributed to higher energy of formation of AL_2O_3 than Si_3N_4 (135).

Force measurements show a reduction in both the cutting and feed forces when machining at higher speeds (Figures 47,48,77 and 99). This could be attributed to the perceived reduction in the tool-chip and tool-workpiece contact length and partly by a drop in the shear strength in the flow zone due to high temperatures generated at high cutting speeds. Evidence of a considerable reduction in the tool-chip contact length have been reported when machining various grades of cast iron with ceramic tools under high speed conditions (86). It has been reported that reduction in the chip-tool contact length reduces the average coefficient of friction due to an increase in the chip thickness ratio (136). Reduction in forces by restriction of contact on the rake face may be a useful technique in some conditions, but in many cases it is not practical because it weakens the tool causing the elimination of the tool clearance face and the additional heat source developed will increase the rate of tool wear.

The large variation in both the cutting and feed forces when machining steel work materials with various grades of ceramic tools at lower cutting speeds up to 200 m/min (Figures 47, 48, 77 and 99), could be attributed to the existence of BUE in various forms under these conditions (Figure 45). The BUE acts like a restricted contact area on the tool, effectively reducing contact on the tool rake face. As already described BUE is dynamic in nature, therefore the forces recorded at lower speeds may be because of the different shapes of BUE in existence (Figure 47). The variation in forces recorded during machining reduced when cutting at high speeds in excess of 300 m/min due to the disappearance of the BUE and complete seizure of the tool-chip and tool-workpiece contact areas during machining.

The plots of the recorded forces show that machining with the silicon nitride based KYON 3000 tools gave the highest component forces while the alumina based KO60 tools gave the lowest forces. KYON 3000 tools also exhibited very high flank wear rate and low tool lives when machining different grades of steel. The rapid flank wear rate radically alters the cutting edge geometry thus increasing the tool-chip and tool-workpiece contact lengths/areas resulting in relatively high forces. The pure oxide (KO60 and mixed oxide (KO90) tools exhibited a slow flank wear rate mainly due to their thermal stability at high speeds where increased temperatures are generated.

There was a general trend towards improved surface finish when machining the work materials with ceramic tools at high speed conditions (Figures 44, 75, 76 and 98). This improvement could therefore, be associated with the perceived increase in temperature at high speeds. The use of higher cutting speed produces an increase in temperature in the primary deformation zone which allows softening of the workpiece surface and an increase in the real area of contact at the tool-workpiece interface. Relative motion between the tool edge and workpiece produces plastic deformation within the surface resulting in a better surface finish. Machining at high speeds resulted in a significant reduction or the complete absence of BUE. This tends to enhance the improvement of the surface finish generated since the intermittent tearing away of the BUE does not occur at high speed conditions.

The plots of the surface roughness values versus cutting speed shows the occurrence of poor surface finish at some high speed conditions. This became the dominant cause for tool rejection especially when machining EN24 and D2 tool steels. Poor surface finish when machining at high speeds could be attributed to the periodic vibration of the machine tool and/ or workpiece during metal cutting and the resulting chatter problems. These irregularities in the machining operation (usually referred to as natural surface finish) cannot be completely eliminated and can only be minimised by the use of expensive high powered and rigid machine tools in a production environment. Poor surface finish generated can also be caused by the ideal surface finish which is a result of the tool geometry (particularly nose radius), the feed rate employed, shape (or geometry) of the cutting tool and the extent of wear. The relative motion at the interface between the tool nose region and smooth areas of the freshly machined workpiece surface generates frictional and adhesive forces because of the interaction of the contacting surface asperities (137). This action tended to worsen the surface finish generated. The use of a 1.6mm nose radius in all the ceramic tools tested means that a large area of the tool nose region will be in contact with the freshly machined workpiece surface resulting in an increased possibility for the interface between the tool nose and the freshly machined workpiece to contact surface asperities, which further deteriorates the surface finish generated. Ideal surface finish is the best surface finish that can be obtained with a given tool-shape and feed rate and can only be achieved if the effect of the natural surface finish is eliminated. The type of chips produced when machining ductile materials, like the steels tested, can adversely affect the surface finish generated.

There was a general deterioration of the surface finish with prolonged machining at all the cutting speed tested, this could be due to an increase in the flank wear associated with prolonged machining. An increase in tool wear leads to an increase in the tool-chip and tool-workpiece contact lengths and the creation of an additional heat source by the reduction or the complete elimination of the tool clearance face by the deformation of the cutting edge. This tends to increase the temperature and the compressive stress/pressure at the tool nose thus developing a zone of intense shear on the worn flank face (Figures 41 and 72). This action could result in the removal of tool particles at the tool nose and the subsequent alteration of the entire cutting edge during the machining operation. The tool particles removed from the tool nose may weld themselves on the newly generated work surface resulting in the worsening of the surface finish. It has been reported that alumina ceramics exhibit a tendency towards welding between the tool and work material (138). The microstructure of the pure oxide (KO60) tools could also cause rapid deterioration of the surface finish when machining the steel work materials. Pure oxide ceramic tools have coarse grain sizes and large pore diameters (Figure 17) which encourage wear by attrition. This produces rough cutting edges which will ultimately affect the surface finish generated.

Debris on the machined surface can also be caused by BUE fragments (Figure 45), fracture of the upper surface of a newly formed chip (Figure 55), and microchips. High stresses and deformation occur before microchips are formed. The size of the microchips are dependent on the stability of the system. A relatively small build up is expected in a rigid machine tool. The stability of BUE when machining ductile materials at low speed conditions have been widely reported (139-141). The effect of the feed and tool profile is completely lost when cutting in the presence of a BUE. The BUE tends to disappear at higher speeds since the material shears plastically thus increasing its ductility. Poor surface finish is generated when cutting at low speeds since the tool cuts intermittently and fractures the chip from the workpiece. This intermittent cutting action usually leaves chatter marks on the machined surface.

The deterioration of the surface finish when machining steel work materials with the silicon nitride based KYON 2000 and KYON 3000 inserts is mainly a result of their relatively high rate of flank wear (especially when cutting at high speeds). Alumina based KO60, KO90 and KYON 2500 ceramic tools are more prone to chipping at the cutting edge during machining as a result of their relatively low hot hardness and fracture toughness. This will in turn lead to the generation of poor machined surfaces.

5.4 EFFECT OF CUTTING TOOL MATERIALS ON WEAR

5.4.1 PURE OXIDE CERAMICS (KO60)

This tool material consists mainly of alumina (99 vol %) and a small amount (1 vol %) of zirconia. The addition of zirconia helps in retarding crack propagation by transforming from a metastable state to a stable state when a crack is initiated thus improving the fracture toughness of the ceramic tool.

The performance of the pure oxide tools when machining three grades of steels at various cutting conditions, is shown in Figures 25, 56 and 78. This grade of ceramic tool generally gave a reliable performance at most speeds tested. Flank wear was the dominant failure mode especially when machining EN24 and D2 Tool Steels at the high speed conditions. This performance could be due to the very low thermal conductivity of the pure oxide ceramic tools at very high temperatures of 1000 degrees centigrade or above (Table 3). These temperatures can only be achieved at or very close to the cutting edge when machining at high cutting speeds in excess of 450 m/min (43). The low thermal conductivity of pure oxide ceramics means that they have greater ability to resist heat transfer from the cutting zone to the insert during high speed machining. This will result in reduced temperatures of the inserts hence minimum and evenly distributed stress at the cutting edge. Flank face wear commonly observed on the used KO60 tools seemed to be mainly dependent upon the temperature generated on both the rake and flank faces. The plucked surfaces which occur on the flank faces mainly at low cutting speeds suggest that attrition wear mechanism was dominant under low speed conditions. Figure 107 is an enlarged view of a KO60 tool used for machining EN24 steel at a low speed of 150 m/min showing attrition wear. The relative movement between the plucked tool particles and the tool surface can cause further dislodging of the tool material by attrition wear mechanism.

An increase in the cutting speed beyond 300 m/min led to a significant increase in the flank wear rate, this may be due to an increase in the temperature at the tool-chip interface, caused by the fast flowing chip under the high speed conditions. These observations may mean that the temperature generated when machining with the pure oxide ceramic tools at high speed controls the flank wear rate. Pure oxide ceramic tool materials are known to be inert to diffusion since they are chemically stable hence consistent performance was obtained when they were used to cut steel work materials.

Thermal cracking was also observed on the flank and rake faces after cutting steel with the KO60 inserts at very high speed conditions (Figure 60). Evidence of thermal cracking in ceramic tools was first reported by Pekelharing (130) when cutting steel. He reported that cracking took place when certain values of speed and feed was exceeded due to tensile stresses produced during cooling as a result of the prior plastic compression of a thin surface layer. Only the cutting speed was altered in this project. The existence of thermal cracks would therefore be associated with the high temperatures generated at very high cutting speeds. The thermal cracks on the rake face lying perpendicular to the cutting edge do not directly affect tool life, since tensile stresses promoting their growth only exist during cooling periods in the cutting cycle (129). Figure 33 shows the fracture of the entire edge of a KO60 tool after machining EN8 steel at 700 m/min. The fracture observed originated from the cracks running parallel and close to the cutting edge. These cracks may have been initiated by fluctuations in cutting loads, rather than by thermal cycling and are usually referred to as "mechanical fatigue cracks". The origins of these cracks is of a thermal nature which may have originated from the pre-existing "comb" cracks (129). Ceramic cutting tool materials generally possess a low tensile strength and are therefore more susceptible to failure by fracture. This is however, compensated for by the use of negative rake geometry which allows the high compressive strength of ceramic tools to be used to advantage. Tensile stresses during cooling are developed by the superficial plastic deformation of a very thin surface layer of the alumina based ceramic tools. The crack growth may be further activated by creep deformation (128) which will relax thermal compressive stresses in the underlying substrate.

Diffusion is widely reported as the dominant wear mechanism at high temperatures achieved when cutting at high speeds (142, 143). These conditions permit chemical reaction or diffusion of elements between the tool and workpiece. Elements such as calcium and silicon play a key role in the diffusion wear of alumina ceramic tools when machining steel (AISI - 4340 type) (144). A similar action seems to be taking place when cutting three grades of steel with Al_2O_3 ceramics tools. The diffused elements, notably calcium and silicon, from the workpiece oxidises on exposure to the atmosphere to Ca0 and SiO_2. These oxides subsequently react with the alumina based tool materials to form an unstable glass-like composite (spinel) which has a low melting point (139). This reaction weakens both the flank and rake faces of the ceramic tools during machining thereby accelerating wear. Diffusion wear on the pure oxide, KO60, tools used for cutting steels occurs when iron (Fe) and silicon (Si) diffuses from the work material into the chip-tool interface and forming their oxides (FeO and $Si0_2$). These oxides react with the alumina to form spinels. Some of the iron and silicon in the interface which does not oxidise invade the pure oxide tools by diffusion and may soften the tool matrix. This action usually combines with the spinel formation causing the weakening of the KO60 tool and increased tool wear.

5.4.2 MIXED OXIDE CERAMIC TOOLS (KO90)

This tool material consists of alumina Al_2O_3 (70 vol %) and a TiC (30 vol %). The crystal structure is shown in Figure 23. The performance of the mixed oxide ceramic tools when machining three grades of steels at various cutting conditions is shown in Figures 25, 56 and 78. This grade of ceramic tools generally gave a reliable performance at most speeds tested especially at intermediate speeds of 250 - 450 m/min. Flank wear was the dominant failure mode especially when cutting EN24 and D2 tool steels. The curves in Figures 27, 61 and 84 show that the average flank wear obeys the general trend; high wear rate at the initial period of cut, then a relatively constant wear rate at intermediate cutting time and rapid rises in the flank wear rate as cutting prolongs. This time related pattern is characteristic of all types of wear mechanisms. At the lower speeds, flank wear is the result of attrition. Plucking took place around the cutting edge, and the plucked particles formed ridges by ploughing the spinel layer formed on the tool/workpiece interface (Figure 67). At the lower speeds, flank wear could be explained as a result of attrition wear mechanism since the temperature generated is not high enough for wear based on diffusion or deformation to be significant. Attrition wear usually occurs if there is a less laminar and more intermittent flow of the work material past the cutting edge. The formation of BUE at the low speed conditions clearly explains this phenomenon. The cutting edges of the mixed oxides ceramic tools were rapidly destroyed by attrition wear when used to cut steel work materials at cutting conditions where BUE was formed. Fragments of tool materials of microscopic size or large lumps were torn from the tool edge. This was due to the localised stresses imposed by the uneven flow of work material. The random tearing of the BUE layer during machining also caused the loss of large fragments of the tool edge. Inadequate rigidity of the machine tool and the use of a slender work piece could cause vibration and chatter during machining as well as the removal of smaller fragments of the tool by attrition wear (43). Tool life can be increased when attrition is dominant by paying special attention to reducing vibration, increasing rigidity and providing adequate clearance angles on the cutting tools. At higher speeds, wear by attrition is not so severe in mixed ceramics because they have smaller grain sizes and contain TiC which increases their resistance to attrition wear.

Severe chipping of the cutting edge was observed when cutting with mixed oxide ceramic tools at moderate speeds (Figure 108). This figure shows a lump of the chipped off tool particle standing proud of the surface. The grooves observed on the tool rake face of such tools may also be caused by the dragging of the chipped off particles at the cutting edge by the underside of the fast flowing chip during machining. TiC is the hardest of all the mixed ceramic constituents (3300 - 4000 HV). The TiC particles are plucked off as a result of attrition wear and the hard particles move on to the underside of the chip to cause abrasion wear. The hard TiC particles may also be dragged between the flank face and the freshly cut surface causing rapid deterioration of the surface finish.

A combination of attrition and diffusion wear mechanisms may be taking place when cutting at intermediate speeds. This can be shown by the smoothly worn and plucked surfaces observed on the mixed ceramic tools under such conditions. The slow plucking of tool particles by attrition wear mechanism could be a result of the inherent vibration of the machine tool and workpiece when cutting at moderate speeds. Diffusion wear mechanism is highly probable at higher speeds because of the high temperatures generated and the large diffusible surface area in the lattice of the mixed ceramic tools. Diffusion wear is common when high temperatures are generated. With mixed oxide ceramic tools carbon is likely to disolve in the TiC and weakens it by causing a volume change.

Cratering was relatively more significant when machining with the mixed oxide ceramic (Figure 34 and 35) although none of the tools were rejected as a result of excessive cratering. The slight crater wear on the mixed ceramic tools was caused due to the presence of TiC in the mixed ceramics which can have a dual effect on the tool. It increases the wear resistance of the tool and also moves the crater closer to the cutting edge (Figure 34). The increase in resistance to crater wear is to some extent, counteracted by the crater being closer to the cutting edge. As the crater approaches the cutting edge, less wear can be borne before the cutting edge is undermined and collapses.

Surface finish was never the tool life controlling factor but was poor in certain cases, like when machining EN8 (Figure 46). This may be caused by the long continuous chips produced when cutting the ductile steel work materials. The continuous chips tend to get tangled on the newly produced surfaces causing further deterioration of the surface finish. Poor surface finish can also be caused by the burr formation on the machined surface. This can be attributed to the significant chipping at the cutting edge geometry.

Component forces were also recorded when cutting steels with mixed ceramic tools (Figures 47, 48, 77a, 77b, 99a and 99b). As can be seen from the figures, a reduction of forces was observed in all cases compared with other ceramic tools used. This reduction of forces was due to the presence of TiC in mixed ceramic tools. The presence of TiC can reduce the contact length and hence the tool face drag forces (86). The reduction in the forces when cutting at high speeds is due to the reduction on the chip-tool contact length and high temperatures near the tool edge which may result in a plastic deformation of the tools at high speeds.

5.4.3 NITRIDE BASED CERAMICS (KYON 2000 , KYON 3000)

It has been demonstrated that Sialon tools are tougher than alumina and can be employed in a wider range of applications. Other major advantages of Sialon is its thermal conductivity and lower coefficient of expansion which provides increased resistance to thermal shock and thermal fatigue compared with alumina (Table 3). The crystal structure of the KYON 2000 tool is shown in Figure 24. The structure consists of the Si_3N_4 cemented by a glassy phase. KYON 3000 tool is similar to Si_3N_4 tool materials but is a Sialon with a relatively low Z value (86).

Flank wear was the major cause of tool failure when machining different grades of steels with the nitride based KYON 2000 and KYON 3000 tools under various cutting conditions (Figures 29, 30, 43, 93 and 94).

A detailed study of the failure modes suggested that three wear mechanisms were operating when machining steels with Sialon tools (KYON 2000 and KYON 3000).

i) Diffusion wear
ii) Attrition wear
iii) Abrasive wear

The attrition wear mechanism was observed at slow speeds below 400 m/min. At higher speeds smooth ridges were observed after cutting with the KYON 2000 and KYON 3000 which indicated the presence of diffusion wear (Figure 43). Jawaid (7) has reported that iron has a tendency to diffuse into nitride based ceramic tools when machining cast iron, it diffuses into glass matrix changing its properties. Such diffusion may have taken place when machining steels, it may however be more pronounced as the temperatures generated during machining of steels are higher than those generated when the machining cast iron. Elements like calcium, sodium and iron have been reported to diffuse into glass matrix of the sialon tools and affect its properties (86). All these may have resulted in diffusion in Si_3N_4 based ceramic tools when machining steels. Short tool lives were recorded when machining with KYON 2000 and KYON 3000 tools when compared with pure oxide (K060, mixed oxide (K090) and silicon reinforced (KYON 2500) ceramic tools and this effect was worsened as speeds were increased (ie. less than a minute when machining at speeds of 400 m/min and above). Short tool lives at high speeds, suggest that diffusion wear was taking place at a relatively fast rate (Figure 109). As the cutting speed increased to above 400 m/min, flank face wear was still the tool life controlling failure mode, but the type of wear mechanism was changed and the tools were more prone to cracks, plucking and chipping (Figures 39, 40, 41, 42, 95, 96 and 72). It is thought that diffusion changed the tool properties and further mechanisms were set into place which resulted in shorter tool life.

The crack initiation may be explained by taking into account the high compressive stresses developed when machining materials like steels at a speed of 400 m/min and above. Force readings obtained when machining with KYON 2000 and KYON 3000 tools followed a traditional pattern (Figures 47, 48, 77a, 77b, 99a and 99b). The forces generally reduced with an increase in cutting speed apart from the region where BUE was suspected. Machining of steels with the nitride based ceramic tools ie. KYON 2000 and KYON 3000 gave the highest cutting forces as can be seen from the force reading figures. This was due to the bigger contact area which was generated due to the severe tool wear at the cutting edge and on the flank face (Figure 94).

5.4.4 SILICON CARBIDE WHISKER REINFORCED CERAMICS (KYON 2500)

Commercial Al_2O_3 - SiC whisker (Al_2O_3 - SiCw) cutting tool materials contain 30 - 40 vol % SiCw with the rest consisting of fine, equiaxed Al_2O_3 and some densification aids such as MgO or Y_2O_3.

These recently introduced SiC whisker-reinforced Al_2O_3 cutting tools exhibit a superior combination of wear resistance and fracture resistance. The flank wear was the dominant failure mode when cutting different grades of steels with the KYON 2500 inserts. The curves in Figures 28, 68 and 86 show that the average flank wear for lower cutting speeds obeyed the general trend, high wear rate at the initial period of cut, then as cutting prolonged, a constant rise in the flank wear rate (Figure 87 shows smooth flank face wear). As the speed was increased further, flank wear rate was increased rapidly to almost straight line in most cases; Figures 69 and 89 show the severe flank face wear observed on the worn KYON 2500 tools. At lower speeds, flank wear is a result of attrition wear mechanisms. Plucking took place around the cutting edge, and the plucked particles formed ridges by ploughing the spinel layer formed at the tool-work interface (Figures 70, 88, 89, 90, 91 and 92). A detailed study of the worn flank faces of KYON 2500 suggest that the wear mechanisms were the same as KYON 2000 and KYON 3000 which has already been discussed, but the addition of whiskers of SiC which improved the hot hardness and toughness of the KYON 2500 may have minimised the flank face wear on the tools. It has been reported that Al_2O_3 - SiCw tool have more than doubled the tool life of the sialon cutting tool materials while the Sialon tool showed significantly higher flank wear than the Al_2O_3 - SiCw tools (145). This can only be explained by the improved and superior combination of wear resistance and fracture resistance of the SiC - whisker reinforcement of Al_2O_3.

Force readings obtained when machining with KYON 2500 tools followed a similar pattern to the ones of pure oxides and mixed oxides (KO60 and KO90) (Figures 47, 48, 77a, 77b, 99a and 99b). The lower cutting forces recorded when cutting with Al_2O_3 -SiC - whisker tools (KYON 2500), especially at high speeds (compared with KYON 2000 and KYON 3000) can only be explained in terms of their superior combination of wear resistance and fracture resistance which may prevent excessive chipping at the cutting edge and a further increase in the tool-chip and tool-workpiece contact length/area.

Surface finish values recorded on the machined surfaces showed that the KYON 2500 insert generally produced better surface finishes than the KYON 2000 and KYON 3000 under most of the cutting conditions tested(Figure 44,46,75 and 98). This result could only be achieved because of higher wear resistance of KYON 2500 tools when machining the steel work materials. The lower surface roughness value obtained when machining D2 tool steel with KYON 2500, which was comparable to those of KO60 and KO90 tools, were due to the better wear resistance of the KYON 2500 and less diffusion between the tool and work materials due to the increased thermal stability of this grade of ceramic tool.

5.5 THE COMPARISON OF THE CERAMIC TOOLS USED WHEN MACHINING DIFFERENT GRADES OF STEELS

In terms of tool life, KO60 gave the best performance under all conditions used for these experiments (Figures 25, 56 and 78). At low speeds of 50 to

200 the tests were stopped after 15 minutes of machining because of very low flank face wear observed and to avoid wasting the work materials available. It is expected that very long tool lives would have been achieved when cutting with the pure oxide ceramic tools under the low speed conditions. At intermediate speeds of 250-450 m/min KO60 tools gave the best tool life, a tool life of 36 minutes was recorded when machining EN24 steel at speeds of 250 m/min, tool life of 35 minutes was recorded when machining D2 tool steel at a speed of 350 m/min and 35 minutes tool life was recorded when machining EN8 steel at a speed of 450 m/min (Figure 100). As cutting speeds was increased, the tool life decreased due to the high temperatures generated at the cutting edges. This coupled with relatively high stresses (both tensile and compressive) as well as low thermal conductivity of the pure oxide ceramic tools resulted in poor tool lives. The low thermal conductivity of the pure oxide ceramic tools will minimise heat conduction from the cutting edge thus increasing the temperature gradient between the hot and cold area of an insert.

In terms of tool life, KO90 were the second best tools when machining different grades of steels: EN8, D2 Tool steel and EN24 (Figures 25, 56 , 78 and 101). KO90 gave better tool life when it was used to machine D2 tool steel (Figure 101) at low speeds of 50 - 250 m/min; due to the presence of TiC which increases their resistance to attrition wear and diffusion wear. At moderate and high speed conditions, tool life was found to be shorter than that given by KO60 tools. This was due to the metallic attraction of titanium to carbon contents of steels. A summary of the wear mechanisms in the mixed ceramic tools show attrition wear as being dominant at lower speeds and diffusion wear became dominant at higher speeds. Other types of wear mechanisms like plucking, cracks and plastic deformation were also observed when machining at high speeds. The optimum cutting conditions for mixed ceramics were obtained at low to moderate speeds.

The SiC whisker reinforced ceramic tools (KYON 2500) gave the third best performance when cutting steels (Figures 25, 56 , 78 and 102). It was found that KYON 2500 could only be used satisfactorily to machine different grades of steel at lower speeds eg. 50 to 300 m/min and as the speed was increased, the tool life was shortened drastically. Better tool life as given by SiC whisker reinforced ceramic tools (KYON 2500) compared with the sialon ceramic tools at lower speeds due to superior combination of wear resistance and fracture resistance. An addition of SiC whiskers to ceramic tools which improved their hot hardness and toughness retarded flank face wear especially at lower speeds in comparison with the sialon ceramic tools (ie. KYON 2000 and KYON 3000). It is true to say that the addition of SiC whiskers to ceramic tools resulted in an increased performance by about two to three fold when machining steel work materials.

Sialon ceramic tools (KYON 2000 and KYON 3000) gave somewhat disappointing results when machining different grades of steels, at speeds above 150 m/min (Figures 103 and 104). There was a slight improvement in performance when this tool was used at lower speeds ie.50, 100, 150 m/min. This can be due to the condition of low temperature and stress taking place when machining with KYON 2000 and KYON 3000 tools. The pure oxide and mixed oxide ceramic tools have higher resistance to diffusion wear than the nitride based ceramic tools because of their higher energy of formation. They therefore form more stable bonds at high temperatures. The low energy of formation of nitride based ceramics explain why shorter tool lives were recorded when cutting with the KYON 2000 tools unlike the pure oxide and mixed oxide ceramic tools. KYON 3000 inserts gave even worse performance than the KYON 2000 at all the conditions used to machine steels. This was because of the lower aluminium oxide percentage in KYON 3000 tools which may have resulted in enhanced diffusion process.

The five different grades of ceramic tools investigated all follow the same wear pattern. Diffusion and attrition wear mechanisms were found to be operating during the machining processes. In the case of pure oxide ceramic (Al_2O_3) tools, attrition wear was the dominant wear mechanism. In particular, extensive chipping and plucking was apparent in the KO60 cutting tools. In the case of mixed oxide (Al_2O_3-TiC) tools having hard TiC particles attrition and diffusion wear mechanisms occurred at slow and higher speeds. Wear of the Si_3N_4 based ceramic (KYON 2000 and KYON 3000) tools was mainly dominated by diffusion wear mechanism. The Al_2O_3-SiC whisker reinforced ceramic (KYON 2500) tools showed an improvement in performance

compared with the sialon tools. They exhibited similar wear mechanisms as the pure oxide and mixed oxide ceramic tools.

CHAPTER 6

6. CONCLUSIONS

1. After detailed machining of different grades of steels (EN8, EN24 and D2 tool steels) using five different grades of ceramic tool (KO60, KO90, KYON 2000, KYON 2500 and KYON 3000), it was established that pure oxide KO60 tools gave the best performance under all the conditions used for these experiments. In terms of tool life, mixed oxide ceramic KO90 tools gave the second best performance when machining different grades of steels. The silicon carbide whisker reinforced ceramic tools (KYON 2500) gave the third best performance when machining steels, especially at low cutting speeds (50 to 300 m/min). Sialon ceramic tools (KYON 2000 and KYON 3000) gave somewhat disappointing results when cutting different grades of steels, especially when machining at speeds above 150 m/min.

2. The best machining conditions in terms of tool life found for the range of experiments were:

	EN8	EN24	D2
Cutting speed (m/min)	150 & 400	250	350
Ceramic tool used	KO60	KO60	KO60
Feed rate (mm/rev)	0.16	0.16	0.16
Depth of cut (mm)	2	2	2
Tool life (min)	20	36	35

3. A comparison of the tool lives between ceramics and carbide (coated and uncoated) when machining steel work materials showed that generally, the alumina based ceramic (KO60, KO90 and KYON 2500) gave longer tool

lives than the carbide tools tested. The carbide tools outperformed the silicon nitride based ceramic tools (KYON 2000 and KYON 3000).

4. In terms of cutting speeds, ceramic tools usually followed the traditional pattern. Good tool lives were recorded at low to intermediate speeds (50 to 450 m/min) and as speed was increased to above 450 m/min, a decline in the tool lives was observed.

5. Ceramic tool lives were affected when machining different steels (EN8, EN24 and D2 tool steels). In general, pure oxide ceramic tools (KO60) gave the best tool lives when used to machine D2 tool steels. This was followed by EN24 and EN8 respectively. Mixed oxide ceramic tools (KO90) followed more or less the same pattern as KO60.

Silicon carbide whisker reinforced alumina ceramic tools (KYON 2500) and nitride based ceramic tools (KYON 2000 and KYON 3000) gave their best performance when used for machining of EN8 followed by D2 tool steel and EN24.

6. Measurement of tool life and rates of wear showed that three major types of failure modes occurred on the ceramic tools.

(a) Failure due to wear on the flank face.

(b) Failure due to fracture or catastrophic failure.

(c) Failure due to generation of poor surface finish on the workpiece material.

7. Depending on the tool material and the condition of machining, the following wear mechanisms were observed:

(a) Attrition wear.

(b) Diffusion wear.

(c) Plastic deformation.

8. The five different grades of ceramic tools investigated all followed the same wear patterns. Diffusion and attrition wear mechanisms were found to be operating during the machining processes. In case of pure oxide ceramic tools (KO60) attrition wear was the dominant wear mechanism. In case of mixed oxide ceramic tools KO90, attrition and diffusion wear mechanisms occurred at lower and higher speeds and abrasion and plastic deformation at intermediate speeds. Silicon nitride based ceramic tools (KYON 2000 and KYON 3000) was mainly dominated by diffusion wear mechanism.

9. Tool fracture occurred mainly when machining with the pure oxide (KO60) and mixed oxide (KO90) ceramic at high speeds above 250 m/min. This may be associated with the lower fracture toughness of the pure and mixed oxide relative to silicon carbide whisker reinforced alumina (KYON 2500) and silicon nitride based ceramic tools (KYON 2000 and KYON 3000).

10. Analysis of cutting forces showed a reduction in both the cutting and feed forces with the rise in cutting speed. This could be attributed to a reduction in the tool chip and tool workpiece contact length.

11. From a study of the microstructure of ceramic tools, it was found that materials having smaller grain sizes gave the best tool life. It was also found that the large glass islands of the nitride based ceramics enhanced attrition and diffusion wear resulting in a shorter tool life.

CHAPTER 7

7.0 SCOPE FOR FUTHER WORK

This research was concentrated on producing a generic data base as well as determining the tool failure modes and wear mechanisms when machining three grades of steel with five different commercially available ceramic tools under various cutting speeds and at a constant feed rate of 1.6 mm/rev and depth of cut of 2 mm. The effect of above parameters on the overall performance of the ceramic tools have explained and documented in detail. Futher investigation may be carried out to study the effect when changing feed rates and depth of cut, this not only will help to understand their effect but will also enhance the data base.

The performance of the recently developed cermet cutting tool materials with improved thermal properties may also be investigated and compared with the data base generated in this project.

Other geometries now available in the ceramic tools may also be studied. During this project experiments were carried out using square inserts only. Rounded inserts are becoming more popular today (due mainly to their better mechanical properties) and may be used in any futher work. Their use may help to eliminate some of the chipping which was observed and hence the tools may give better performance.

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Increased growth	No effect	Retarded growth
Ti	Gu	F Sr V
Nb	Y	Cl Ba Mg
Mn	P	Br La
Cu	Fe	I Cr
Ge	Th	Sb Si
	Ce	K Su
	Zr	Na Ca

Table 1 **The sintering aids**

Material Properties		Hardmetals P10	Ceramic Al_2O_3
Hardness (HV)	20°c	1400	2200
	1000	600	1500
Tensile α B Mpa	20	800	200
Strength	1000	600	200
Coeff of μ	20	0.6	0.15
Friction	1000		
Oxidation	20	no	no
	1000	severe	no

Table 2 **Properties of ceramic and cemented carbide tools at both room and elevated temperatures**

GRADE	Pure Oxide KO60	Mixed oxide KO90	Silicon nitride KY2000 & KY3000	SiC Whisker Al_2O_3 KY2500
Nominal Composition (Vol %)	Al_2O_3 >99 ZrO_2<1	Al_2O_3=70 TiC=30	Sialon	Al_2O_3=60-70% SiC_w=30-40%
Density g/cm^3	3.99	4.29	3.26	3.74
Hardness vhn-1Kg (Kg/mm^2)	1800	2230	1870	1970
Hot hardness vhn-1Kg Load	800	900	1230	
Toughness, K1c (Mpa m3/2)	4.3	4.5	6.5	6
Young's Modulus E (GPa)	390	416	304	57* 10^3 psi
Thermal conductivity cals/cm s°K Room temperature 1000°C	 0.0708 0.0181	 0.0517 0.0236	 0.1284 0.0203	
Termal expansion Co (10^{-6}/°C) room temp 1000 °C	8.2	8.6	3.1	
Bend strength (MPa)	700	910	750	

Table 3 The composition and properties of ceramic tools

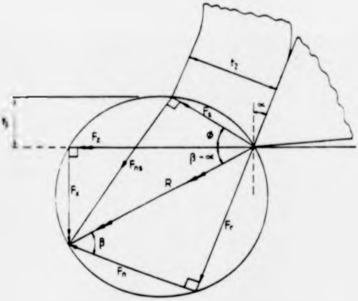

Figure 1 System of Forces on Orthogonal Cutting

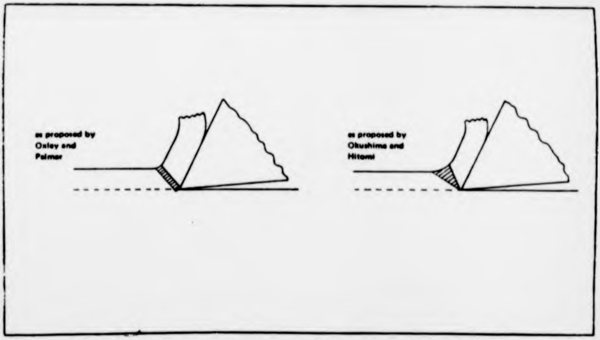

Figure 2 Thick Shear Zone Models

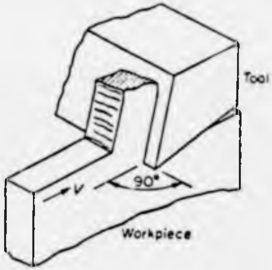

Figure 3 Orthogonal cutting– Cutting edge perpendicular to cutting velocity

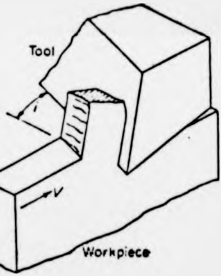

Figure 4 Oblique cutting– Angle of inclination of cutting edge i

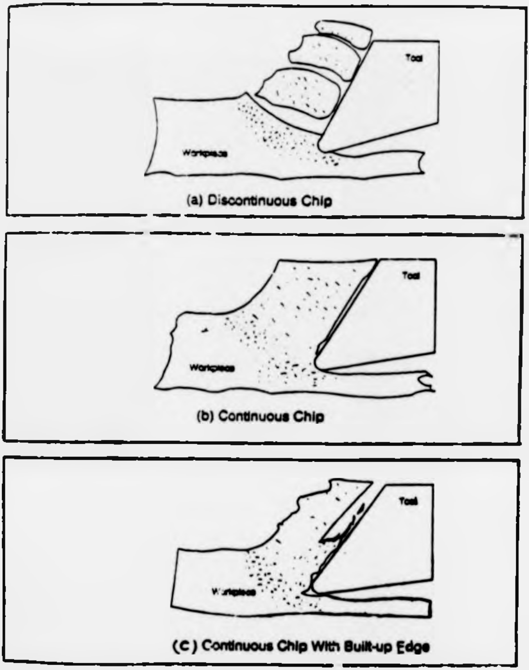

Figure 5 Types of Chip Produce during Metal Cutting

$$\text{C.L.A.} = \frac{A_1 + A_2 + A_3 + \ldots + A_n}{L}$$

$$= \frac{\Sigma A}{L}$$

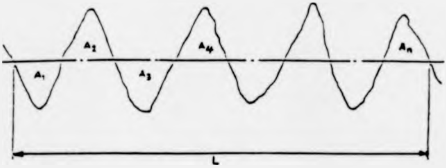

Figure 6 Graphical representation of C.L.A

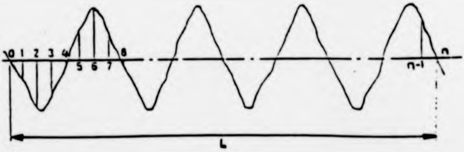

Figure 7 Graphical representation of R.M.S.

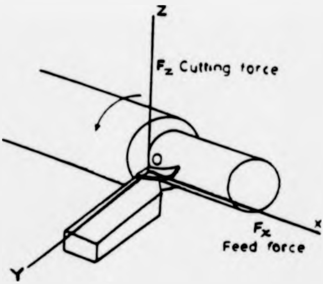

Figure 8 Three component forces acting on a cutting tool

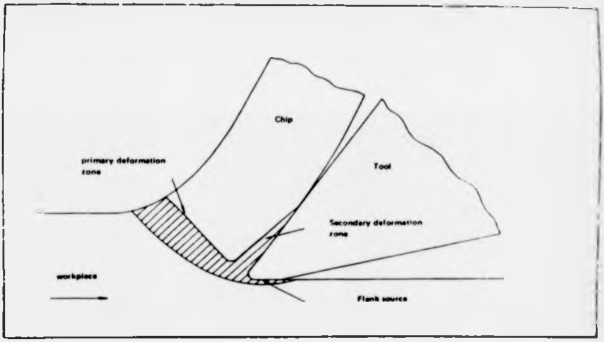

Figure 9 Generation of Heat in Orthogonal Cutting

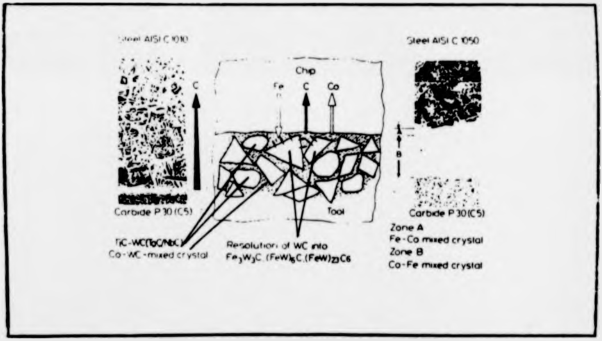

Figure 10 Simplified Model of the Diffusion Processes

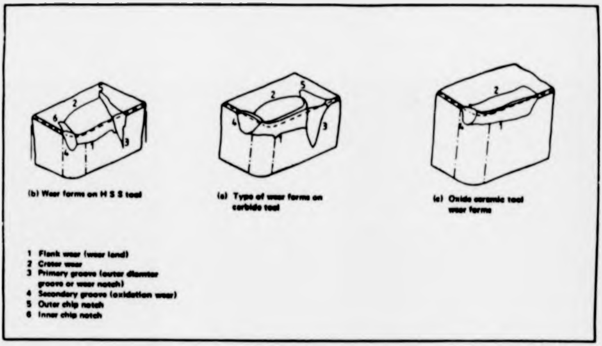

Figure 11 **Wear forms on cutting tools**

Co %	Mean Wc Grain size µm	Hardness HV30	TRS (MPa)	TRS tonf/in^2	Comp. Strength (MPa)	Comp. Strength tonf/in^2	Young's Modulus (GPa)	Young's Modulus tonf/ in^2*10^3	Fracture Tough. Kic MNm^3	Specific Gravity MNm$^{-3/2}$
3	0.7	2020	1000	65						
	1.4	1820							8	
6	0.7	1800	1750	113	4550	295				
	1.4	1575	2300	148	4250	275	630	40.7	10	14.95
	0.7	1670	2300	148						
9	1.4	1420	2400	156	4000	260	588	38	13	14.75
	4	1210	2770	179	4000	260				
15	0.7	1400	2770	179			538	34.8		
	1.4	1160	2600	168	3500	225			18	14

Figure 12 **Properties of WC-Co alloys (after Trent[41])**

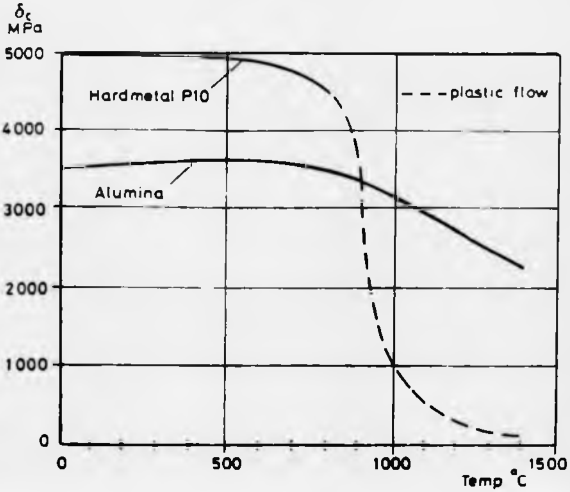

Figure 13 **Difference between the compressive strength of ceramic and carbide (P10) tools at room and elevated temperatures**

Figure 14 **Microstructure of plain carbon steel (EN8) x200**

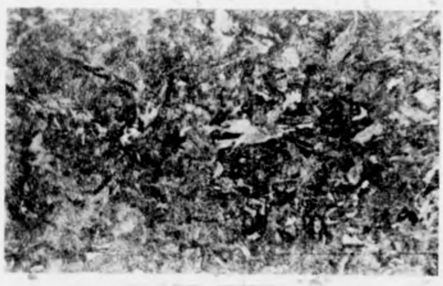

Figure 15 **Microstructure of medium carbon steel (EN24) x150**

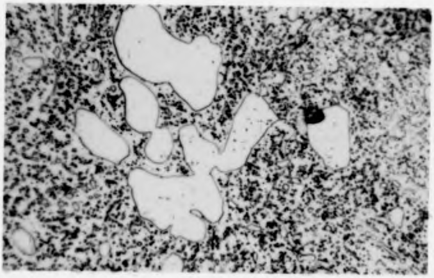

Figure 16 **Microstructure of hardened steel (D2 tool steel) x150**

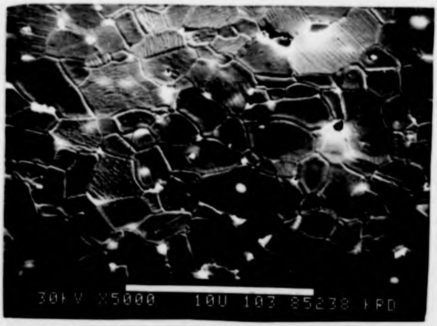

Figure 17 **Microstructure of pure oxide ceramic tool (KO60)**

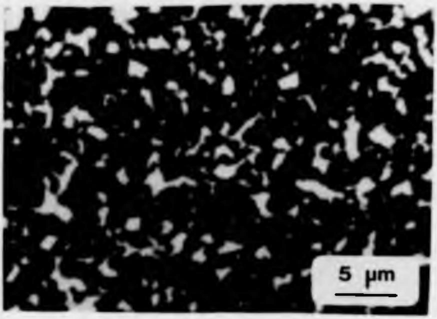

Figure 18 Microstructure of mixed oxide ceramic tool (KO90)

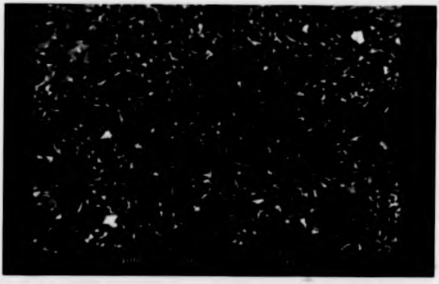

Figure 19 Microstructure of nitride based ceramic tool (KYON 2000)

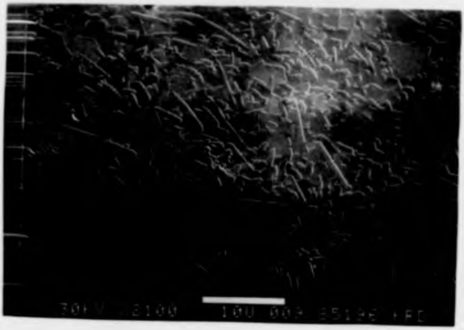

Figure 20 **Microstructure of silicon carbide whisker reinforced ceramic tool (KYON 2500)**

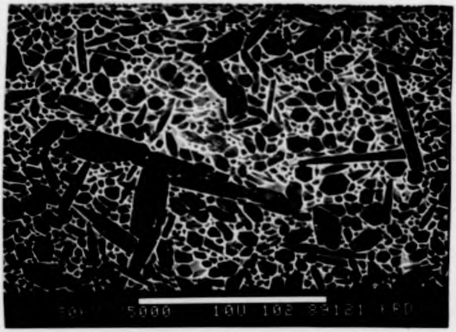

Figure 21 **Microstructure of nitride based ceramic tool (KYON 3000)**

Figure 22 Crystal structure of KO60 tools

Figure 23 Crystal structure of KY90 tools

Figure 24 Crystal structure of KYON 2000 tools

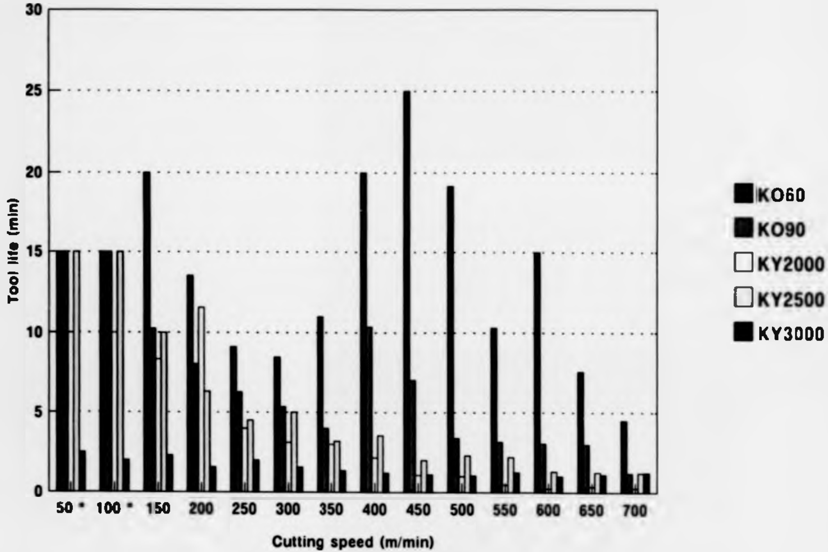

Figure 25 summary of tool lives (min) Vs cutting speeds (m/min)
when machining EN8 with ceramic tools
(*) Test were terminated after 15 mins

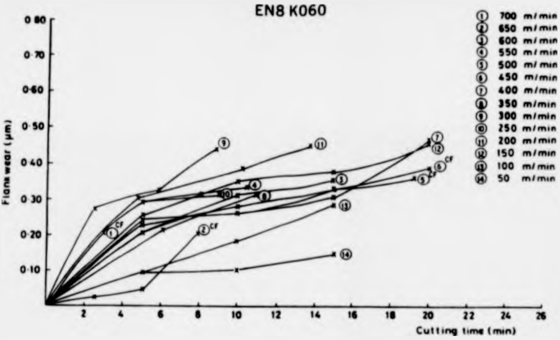

Figure 26 Average flank wear Vs cutting time when machining plain carbon steel (EN8) with pure oxide ceramic (KO60) tools

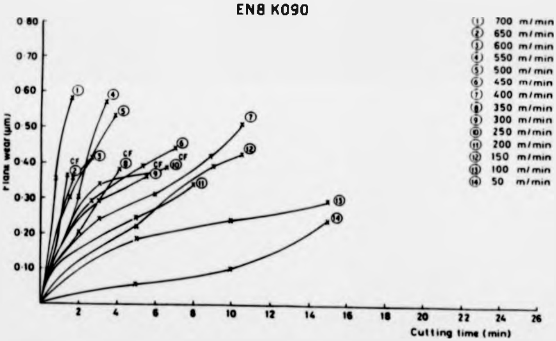

Figure 27 Average flank wear Vs cutting time when machining plain carbon steel (EN8) with mixed oxide ceramic (KO90) tools

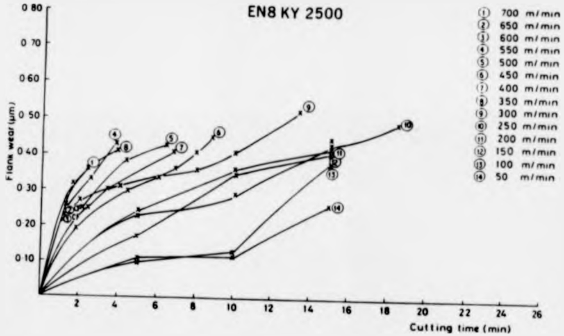

Figure 28 **Flank wear Vs cutting time when machining plain carbon steel (EN8) with silicon carbide whisker reinforced alumina ceramic (KYON 2500) tools**

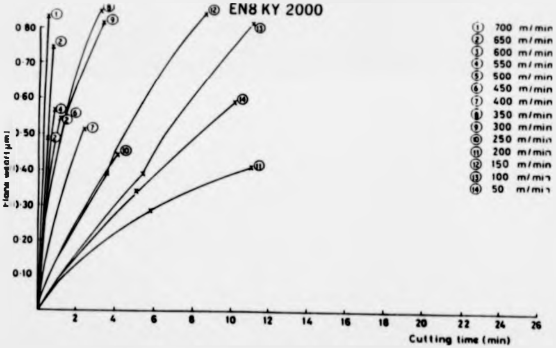

Figure 29 **Flank wear Vs cutting time when machining plain carbon steel (EN8) with sialon ceramic (KYON 2000) tools**

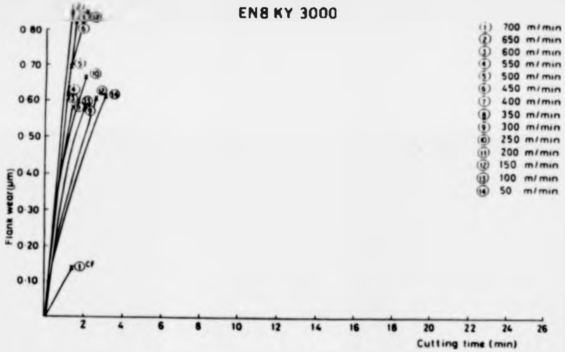

Figure 30 Flank wear Vs cutting time when machining plain carbon steel (EN8) with sialon ceramic (KYON 3000) tools

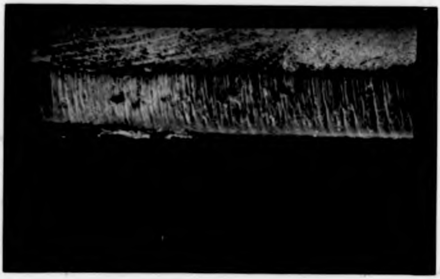

Figure 31 Showing pure oxide ceramic tool (ko60) when machining EN8 steel at speed of 400 m/min

Figure 32 Showing ridges formed on pure oxide ceramic tool (KO60) when machining EN8 steel at speed of 600 m/min

Figure 33 Showing general view of fracture surface of mixed oxide ceramic tool (KO90) when machining EN8 steel at speed of 700 m/min

Figure 34 General view of mixed oxide ceramic tool (KO90) when used to machine EN8 steel at the speed of 100 m/min

Figure 35 Chipping of tool particles when machining EN8 steel with KO90 at speed of 100 m/min

Figure 36 Plucking of tool particles on the flank face of KO90 tool when machining EN8 steel at the speed of 100 m/min

Figure 37 Severe chipping at the cutting edge of Kyon 2500 tool when machining EN8 steel at the speed of 700 m/min

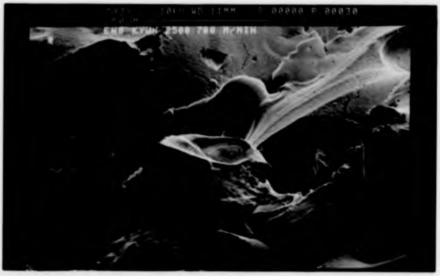

Figure 38 Enlarged view of a fractured surface of KYON 2500 when machining EN8 at the speed of 700 m/min

Figure 39 Cracks and plucking of the worn flank face of KYON2000 when cutting EN8 steel at the speed of 100 m/min

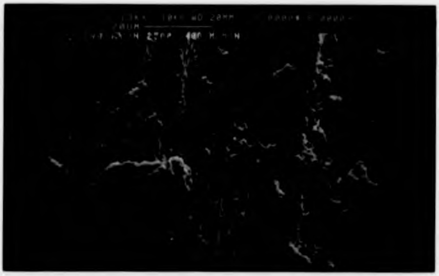

Figure 40 Bottom of groove after machining EN8 steel with KYON 2000 at 400 m/min

Figure 41 Large cracks on the flank face of KYON 2000 after machining EN8 at the speed of 700 m/min

Figure 42 Plucking between the ridges on the worn flank face of KYON 3000 when machining EN8 at 100 m/min

Figure 43 Showing the cutting edge of worn KYON 3000 tool after machining EN8 at a speed of 700 m/min

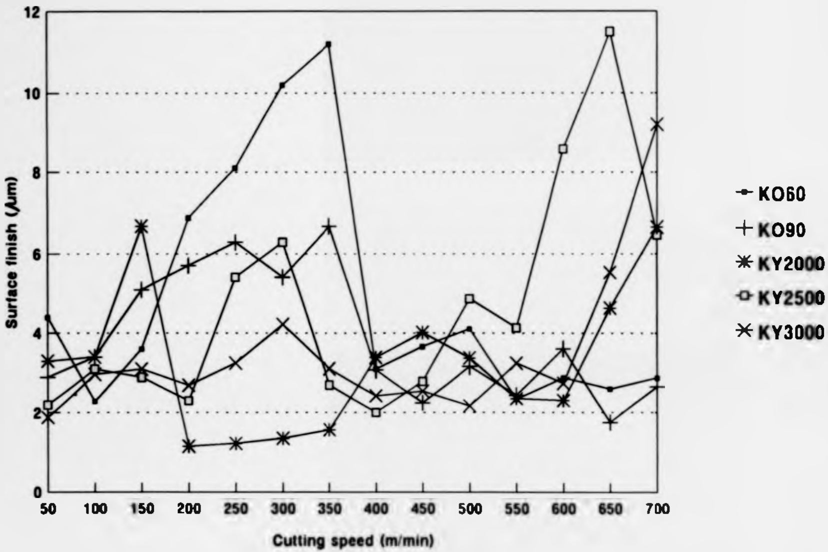

Figure 44 Surface roughness (μm) Vs cutting speed (m/min) when machining EN8
At the time of tool failure

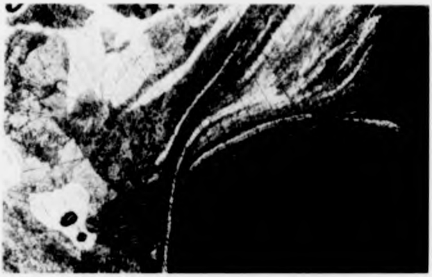

Figure 45 Quick stop sample showing BUE when machining EN8 with KO90 at a speed of 50 m/min

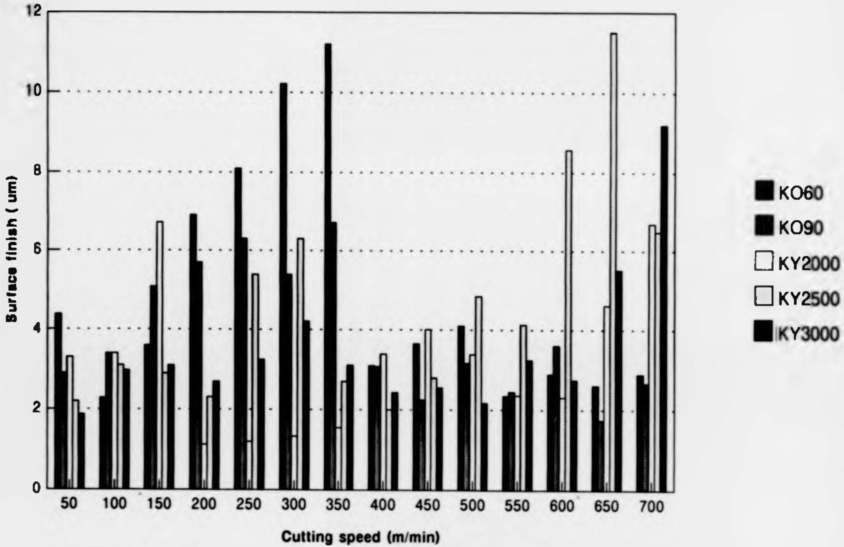

Figure 46 Surface roughness (um) Vs cutting speed (m/min) when machining EN8
At the time of tool failure

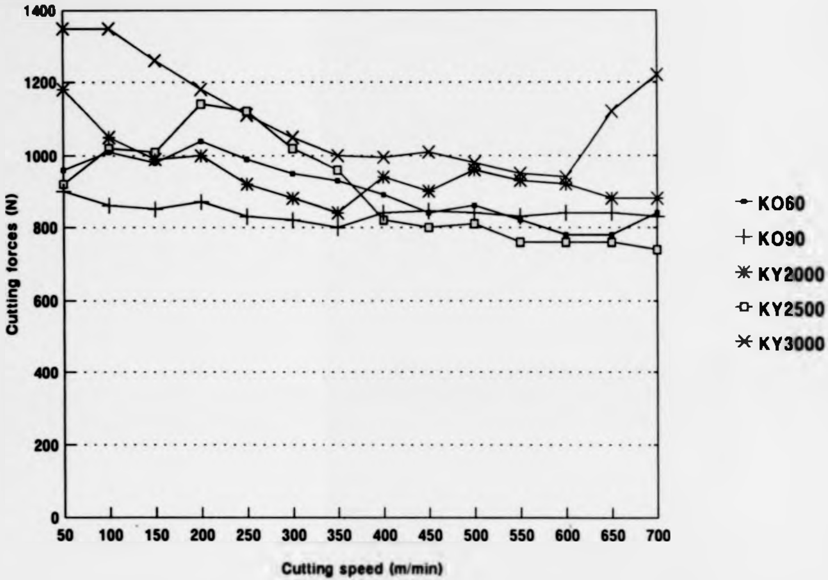

Figure 47 Cutting force (N) Vs cutting speed (m/min) when machining EN8 with ceramic tools

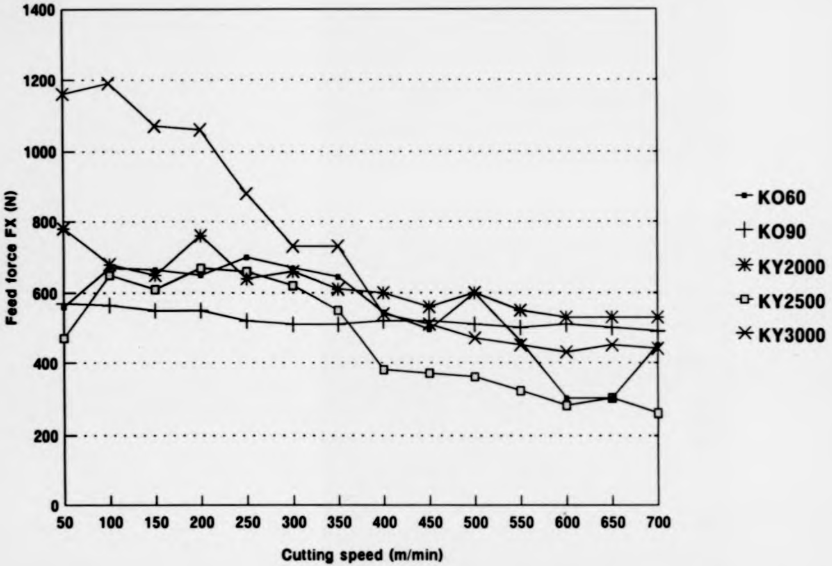

Figure 48 Feed forces (N) Vs cutting speeds (m/min) when machining EN8 with ceramic tools

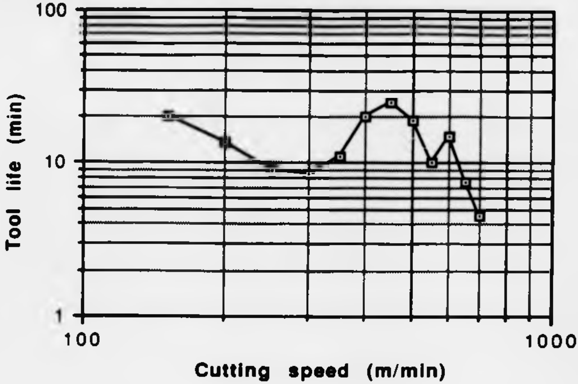

Figure 49 Taylor's tool life curve when machining EN8 with pure oxide ceramic (KO60) tools

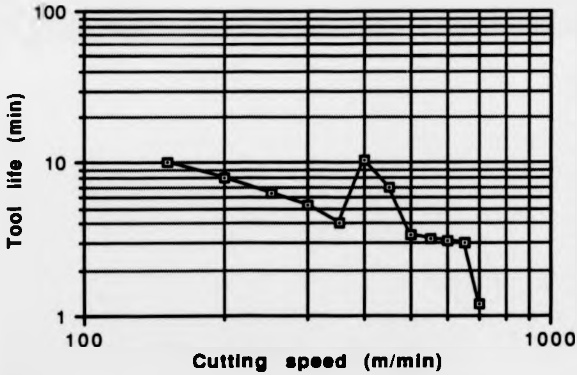

Figure 50 Taylor's tool life curve when machining EN8 with mixed oxide ceramic (KO90) tools

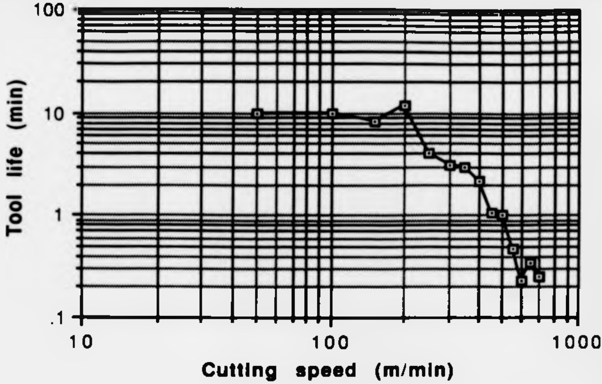

Figure 51 Taylor's tool life curve when machining EN8 with nitride based ceramic (KYON 2000) tools

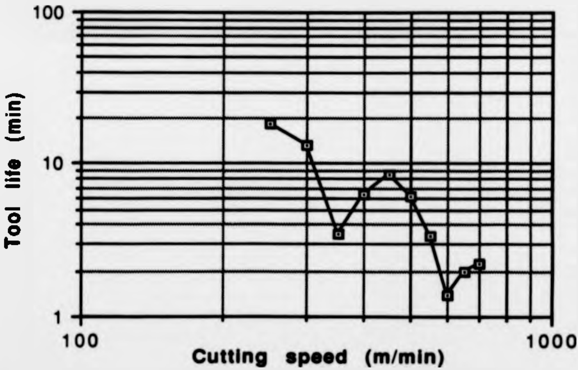

Figure 52 Taylor's tool life curve when machining EN8 with silicon carbide whisker reinforced alumina ceramic (KYON 2500) tools

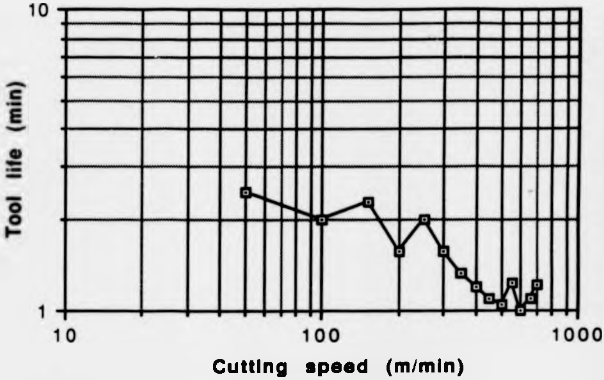

Figure 53 Taylor's tool life curve when machining EN8 with nitride based ceramic (KYON 3000) tools

Figure 54 Quick stop test showing formation of the chip and distortion of grain boundries when machining EN8 with KO60 tool at a speed of 100 m/min

Figure 55 Quick stop test showing enlarged section of the newly formed chip and fracture of the upper surface when machining EN8 with KO90 at 100 m/min

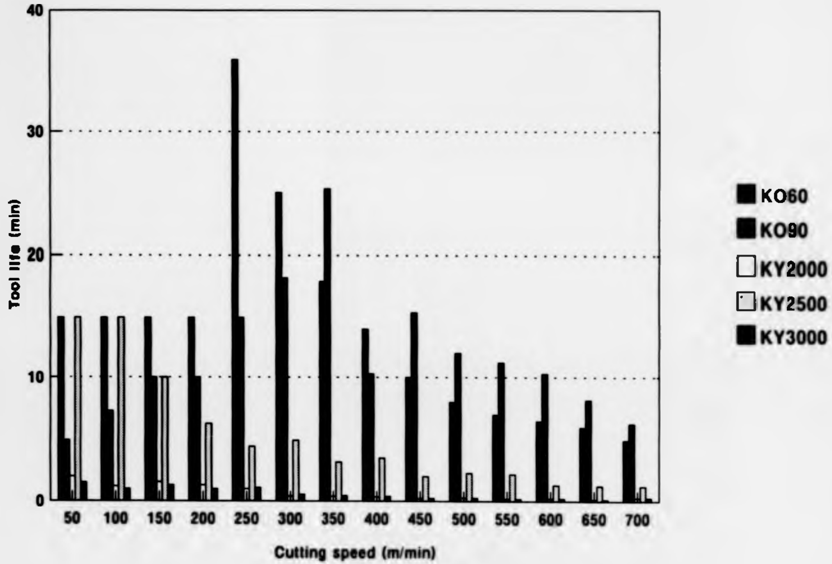

Figure 56 Summary of tool lives (min) Vs cutting speeds (m/min) when machining EN24 with ceramic tools

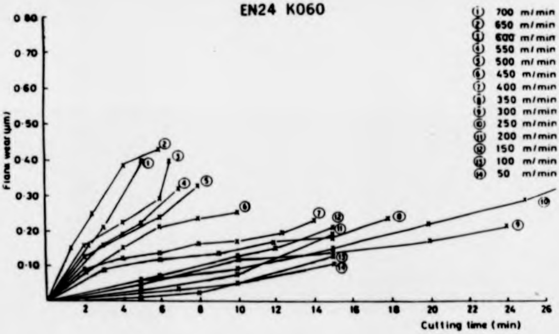

Figure 57 Flank wear Vs cutting time when machining alloy steel (EN24) with pure oxide ceramic (KO60) tools

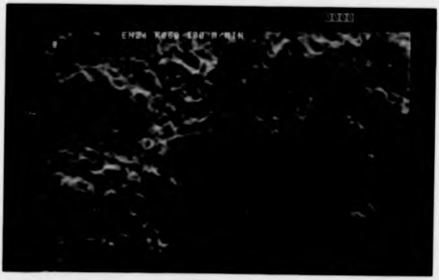

Figure 58 Plucked surface on the worn flank face of the KO60 tool when machining EN24 at a speed of 100 m/min

Figure 59 Showing plucked surface on worn flank face of KO60 tool after machining EN24 at speed of 400 m/min

Figure 60 Portion of the flank face of KO60 tool surrounded by cracks when machining EN24 steel at a speed of 700 m/min

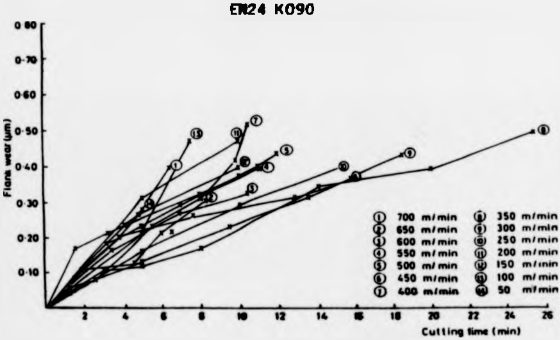

Figure 61 Flank wear Vs cutting time when machining alloy steel (EN24) with mixed oxide ceramic (KO90)

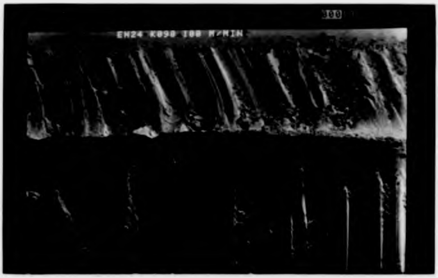

Figure 62 Irregular and rough surfaces on worn KO90 tool after machining EN24 steel at a speed of 100 m/min

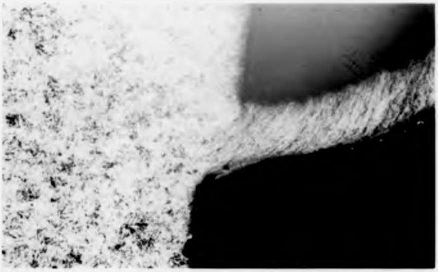

Figure 63 Quick stop test showing the existance of BUE after machining EN24 with KYON 2000 at a speed of 100 m/min

Figure 64 The uneven wear on the flank face of KO90 tool after machining EN24 steel at a speed of 100 m/min

Figure 65 Showing cracks on the flank face of KO90 tool after machining EN24 steel at a speed of 700 m/min

Figure 66 Showing chipping or flaking of the cutting edge of KO90 tool after machining EN24 at a speed of 400 m/min

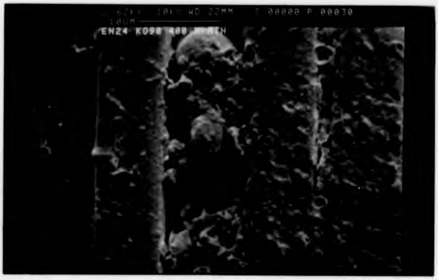

Figure 67 Showing loosely bonded tool particles ready for plucking between the grooves on the flank face

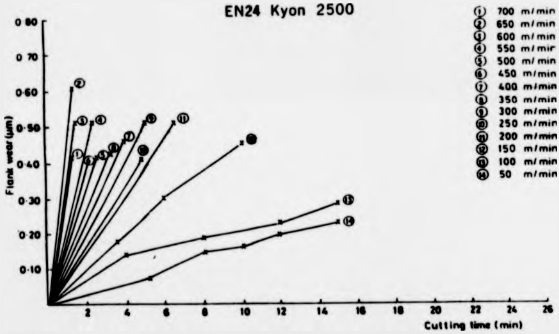

Figure 68 Flank wear Vs cutting time when machining alloy steel (EN24) with silicon carbide whisker reinforced ceramic (KYON 2500) tools

Figure 69 General view of KYON 2500 tool after machining EN24 at a speed of 400 m/min

Figure 70 Close up view of worn flank face revealing cracks close to the tool nose

Figure 71 Showing cracks after machining EN24 with KYON 2500 at a low speed of 100 m/min

Figure 72 Showing shearing action in addition to severe chipping after machining EN24 with KYON 2500 at a speed of 400 m/min

Figure 72a Showing severe cracks on the worn flank face of KYON 2000 after machining EN24 at a speed of 400 m/min

Figure 72b Showing severe chipping and plucking after machining EN24 with KYON 2000 at a speed of 100 m/min

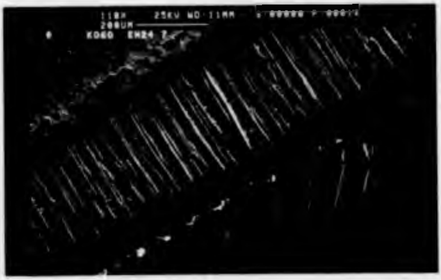

Figure 73 Typical crater wear after machining EN24 with pure oxide ceramic tools (KO60)

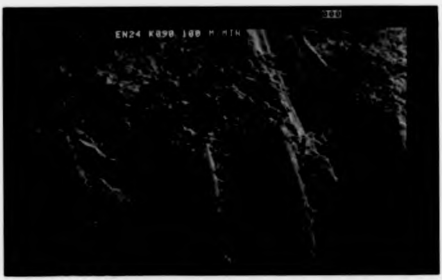

Figure 74 Magnified view of the worn rake face of KO90 after machining EN24 at speed of 100 m/min showing severe wear and extent of plucking

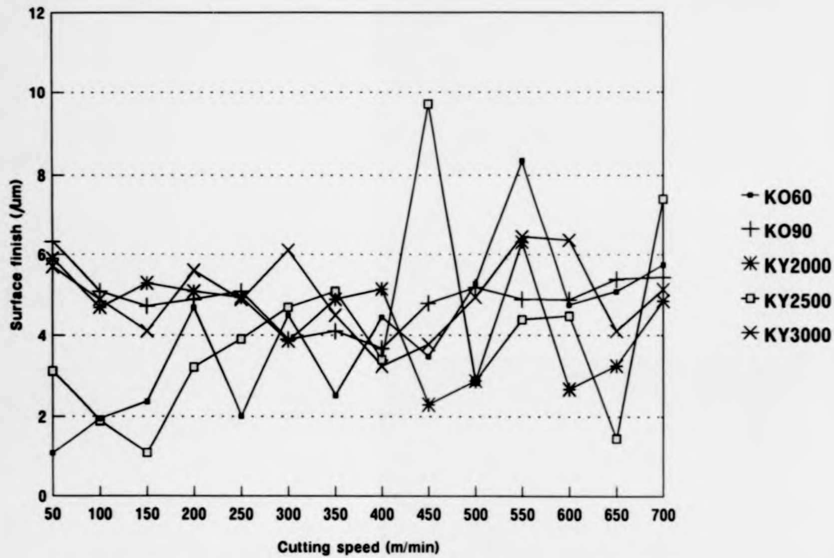

Figure 75 Summary of surface roughness (µm) Vs cutting speed (m/min) when machining EN24 with ceramic tools (at the time of tool failure)

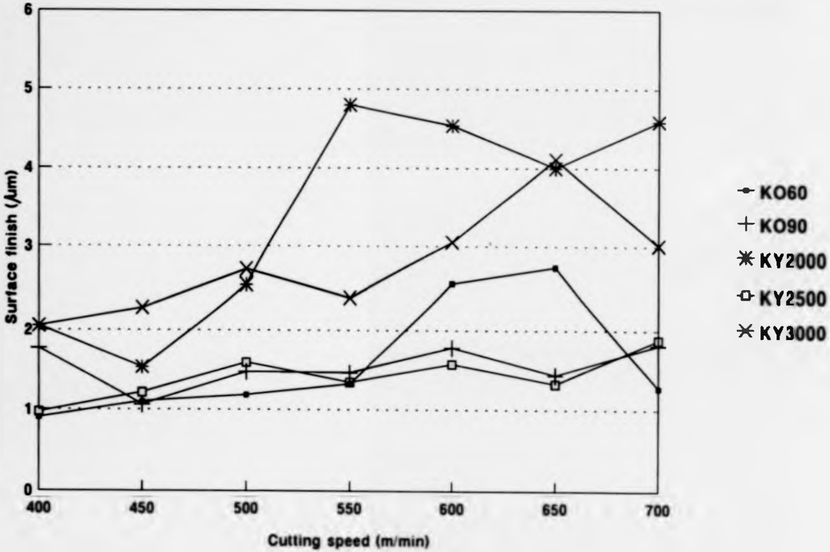

Figure 76 Surface roughness (µm) Vs cutting speed (m/min) when machining EN24 with ceramic tools (after 15 seconds of cut)

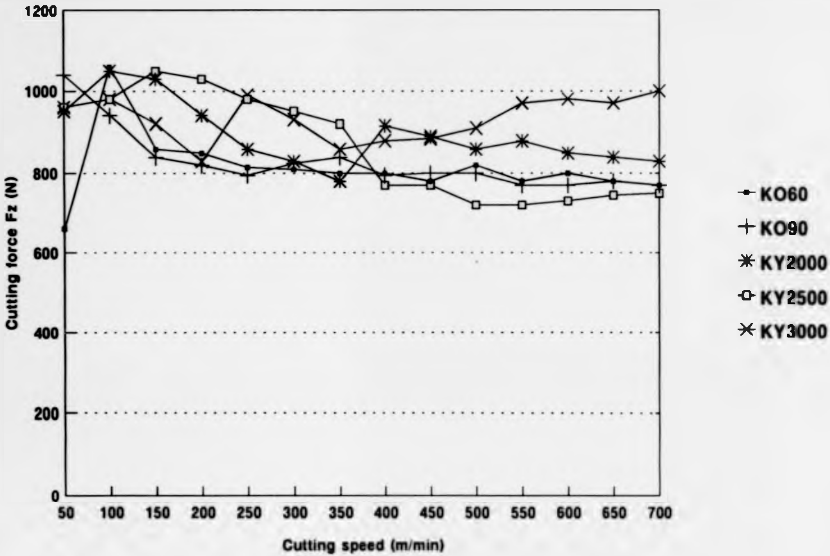

Figure 77a Cutting force Fz (N) Vs cutting speed (m/min) when machining EN24 with ceramic tools

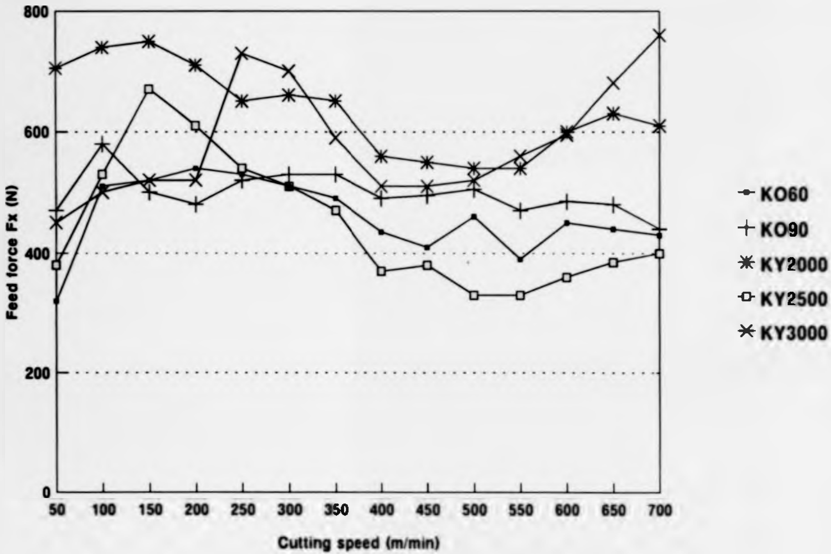

Figure 77b Feed force Fx (N) Vs cutting speed (m/min) when machining EN24 with ceramic tools

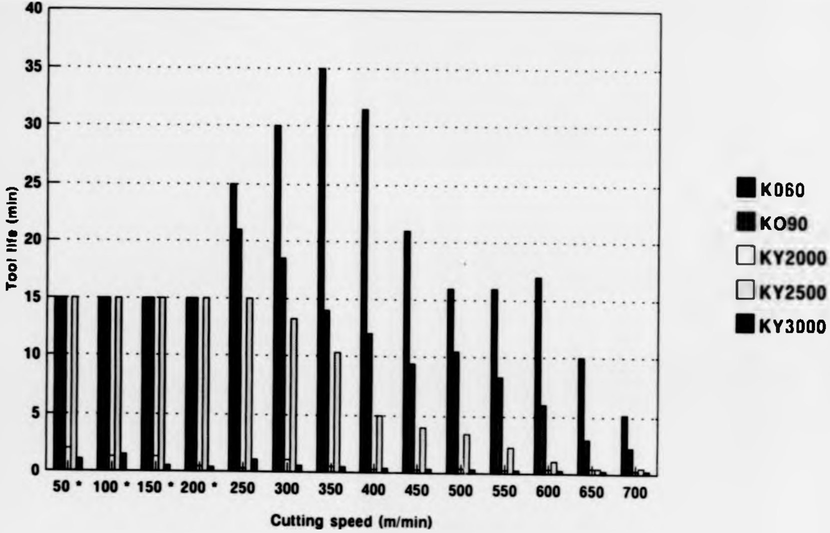

Figure 78 Summary of tool lives (min) Vs cutting speeds (m/min) when machining D2 tool steel with ceramic tools
(*) test terminated after 15 mins

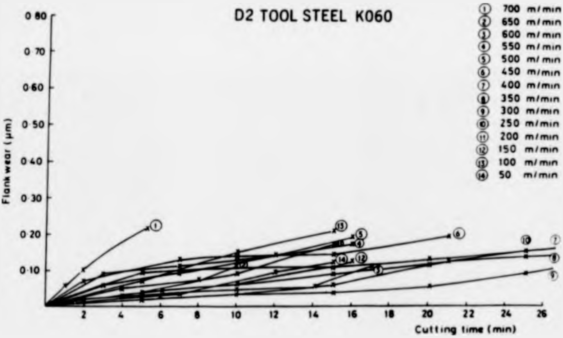

Figure 79 Flank wear Vs cutting time when machining hardened steel (D2 tool steel) with pure oxide ceramic (KO60) tools

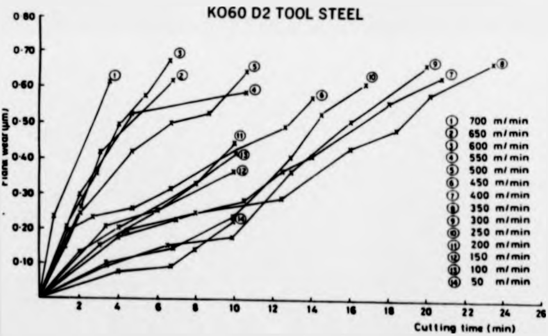

Figure 80 Maximum flank wear Vs cutting time when machining hardened steel (D2 tool steel) with pure oxide ceramic (KO60) tools

Figure 81 Showing the extent of flaking at the cutting edge of KO60 tool after machining D2 tool steel at a speed of 100 m/min

Figure 82 Showing a deep crack running from the tool nose to the flank face and extensive plucking

Figure 83 Showing chipping at the cutting edge of KO60 tool after machining D2 tool steel at a speed of 700 m/min

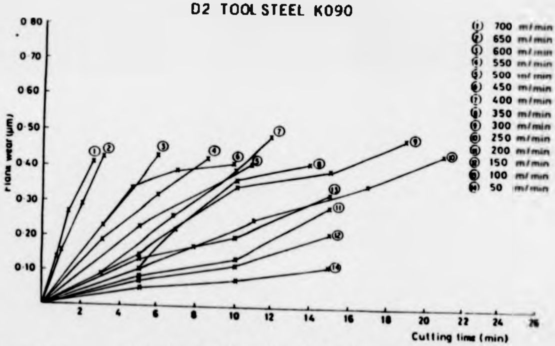

Figure 84 Flank wear Vs cutting time when machining hardened steel (D2 tool steel) with mixed oxide ceramic (KO90) tools

Figure 85 Showing the extent of wear on both rake and flank faces as well as plucking

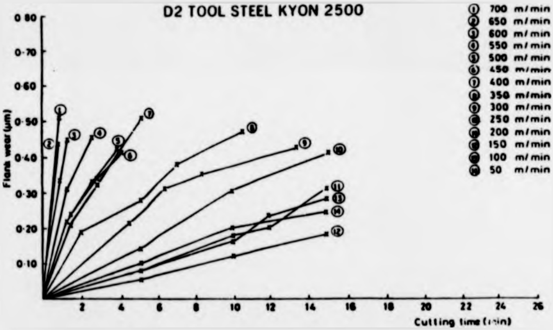

Figure 86 Flank wear Vs cutting time when machining hardened steel (D2 tool steel) with silicon carbide whisker reinforced ceramic (KYON 2500) tools

Figure 87 Showing pronounced ridges on the flank face after machining D2 tool steel with KYON 2500 at a speed of 100 m/min

Figure 88 Close up view of ridges (above figure) showing plucking

Figure 89 Showing a combination of flaking at the cutting edge and plucking and cracks on the flank face

Figure 90 Close up view of above figure showing severely worn flank face

Figure 91 Section of the worn flank face showing wear of the tool particle

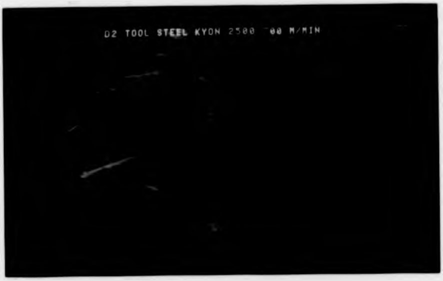

Figure 92 Magnified view of wornk flank face showing the extent of dislodging of the tool particles

Figure 93 Showing ridges on the worn flank face of KYON 2000 when machining D2 tool steel at a speed of 100 m/min

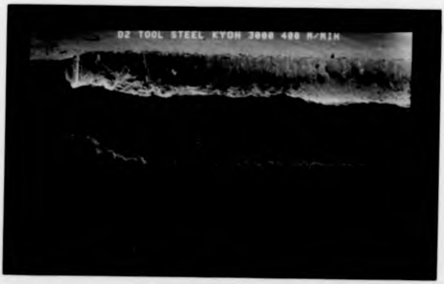

Figure 94 Showing erosion of the tool materials at the primary cutting edge, crater wear and flank face wear

Figure 95 Showing extensive plucking of tool particles after machining D2 tool steel with KYON 3000 at a speed of 400 m/min

Figure 96 Showing cracks on the worn flank face of KYON 3000 tool

Figure 97 Showing erosion of tool particles at the cutting edge of the tool

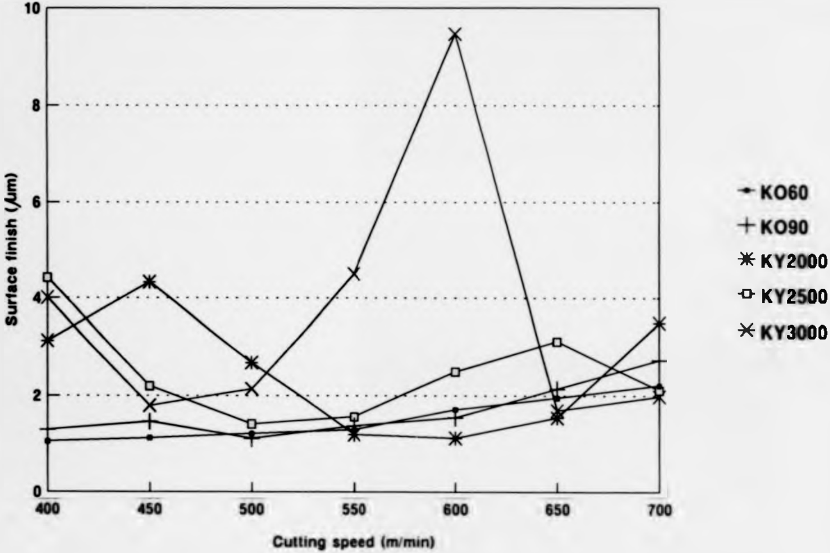

Figure 98 Surface roughness (µm) Vs cutting speed (m/min) when machining D2 tool steel with ceramic tools (after 15 seconds of cut)

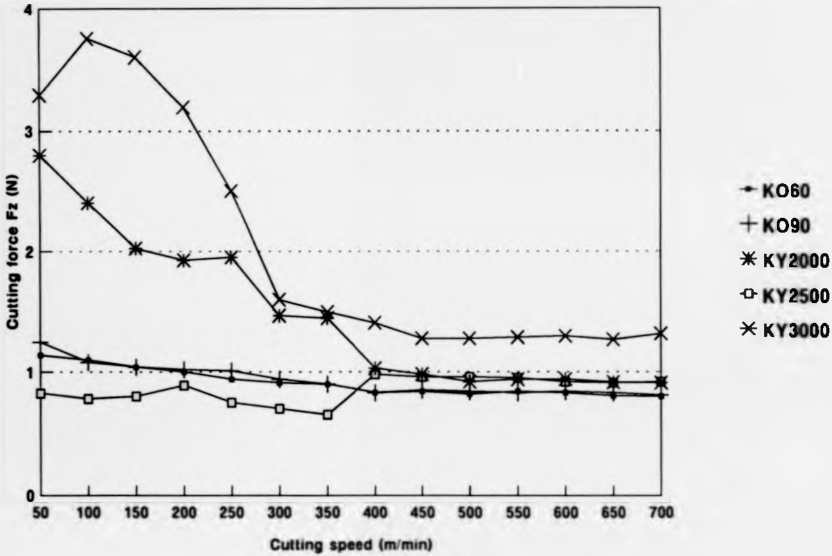

Figure 99a Cutting force F_z (N) Vs cutting speed (m/min) when machining D2 tool steel with ceramic tools

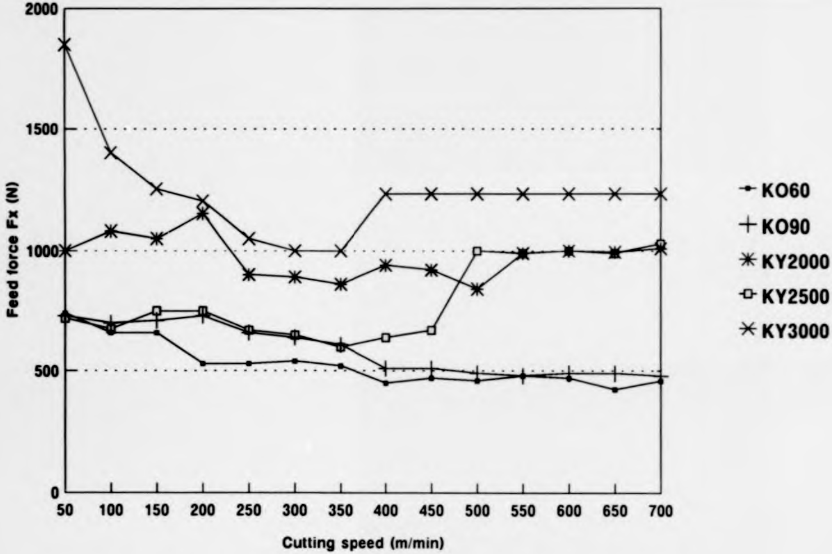

Figure 99b Feed force Fx (N) Vs cutting speed (m/min) when machining D2 tool steel with ceramic tools

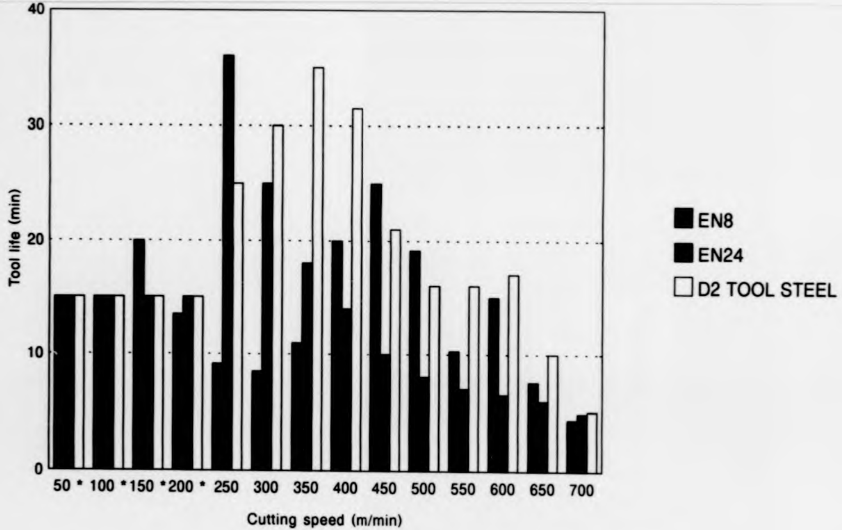

Figure 100 Summary of tool life (min) Vs cutting speed (m/min) when machining EN8, EN24 and D2 tool steel with pure oxide ceramic tool (KO60)
(*) test terminated after 15 mins

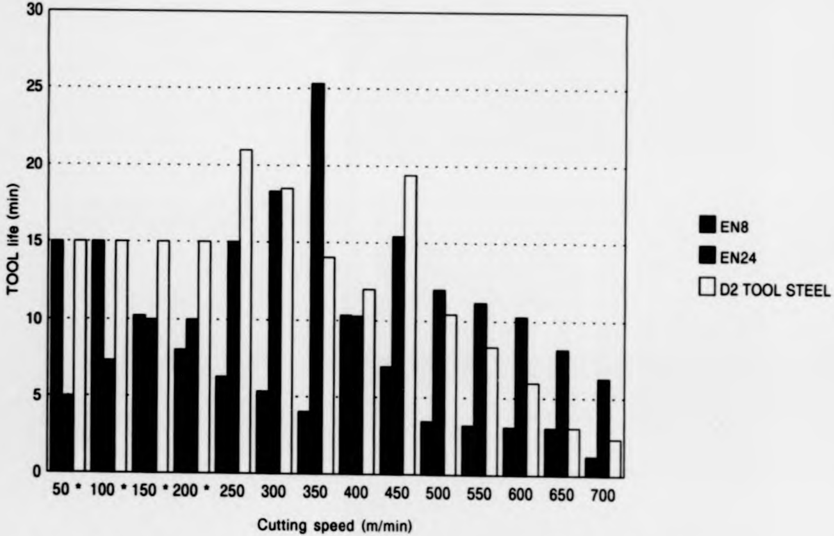

Figure 101 Summary of tool life (min) Vs cutting speed (m/min) when machining EN8, EN24 and D2 tool steel with mixed oxide ceramic tool (KO90)

(*) test terminated after 15 mins

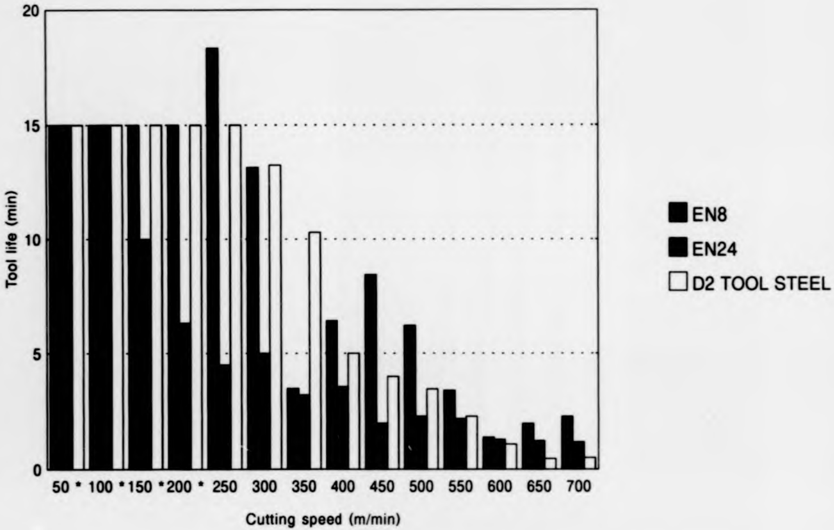

Figure 102 Summary of tool life (min) Vs cutting speed (m/min) when machining EN8, EN24 and D2 tool steel with silicon carbide whisker reinforced ceramic tool (KYON 2500)
(*) test terminated after 15 mins

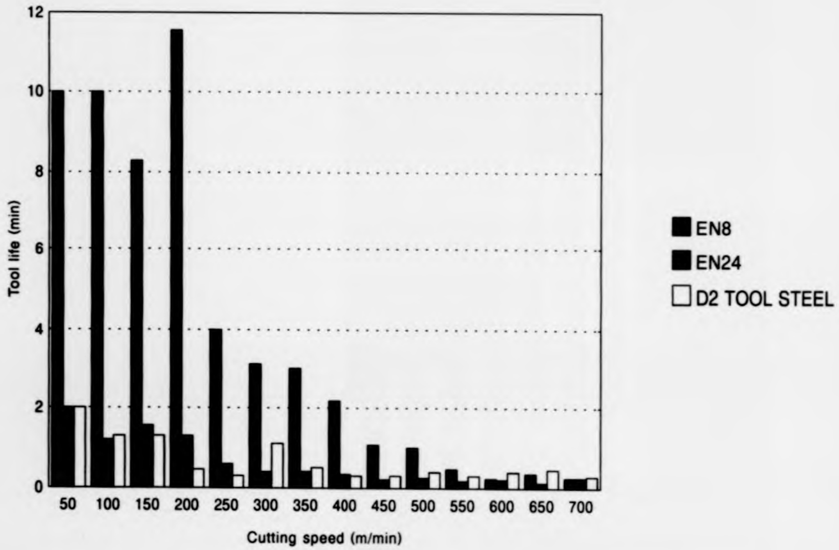

Figure 103 Summary of tool life (min) Vs cutting speed (m/min) when machining EN8, EN24 and D2 tool steel with nitride based ceramic tool (KYON 2000)

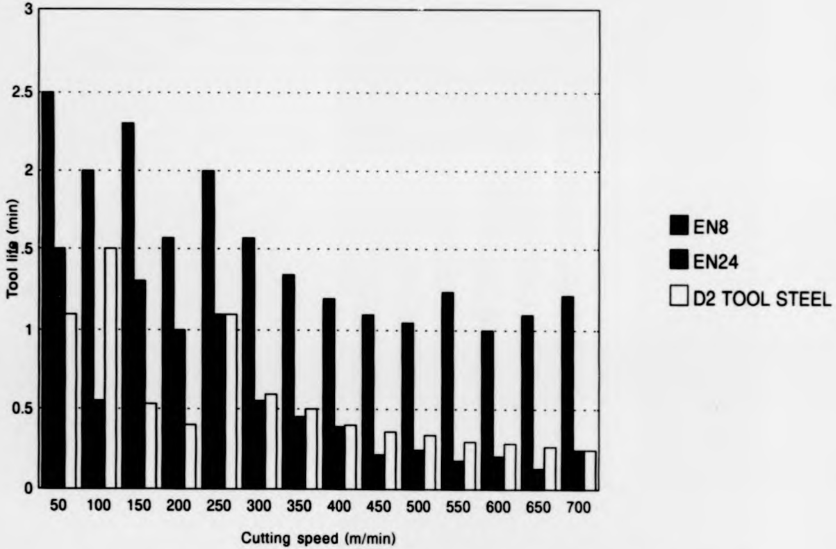

Figure 104 Summary of tool life (min) Vs cutting speed (m/min) when machining EN8, EN24 and D2 tool steel with nitride based ceramic tool (KYON 3000)

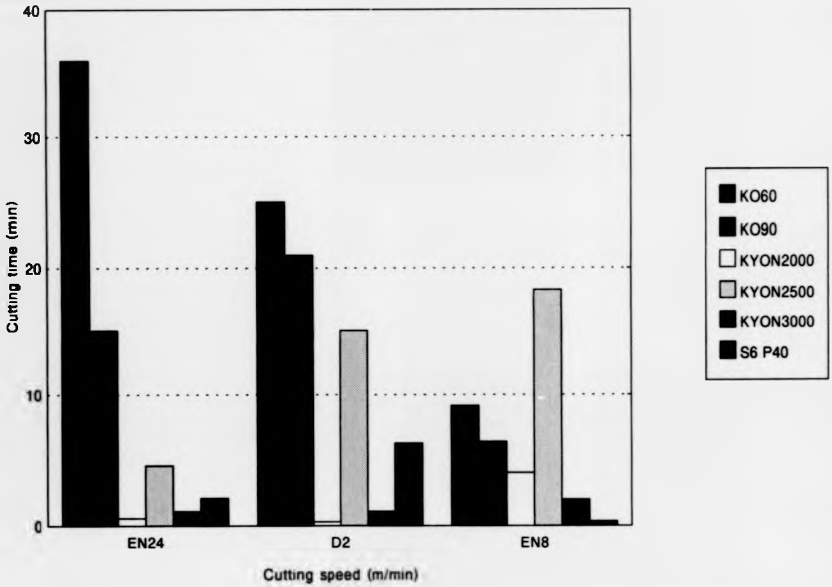

Figure 105 Comparison tool life (min) between the ceramic tools and uncoated carbide (S6P40) tool at speed of 250 (m/min)

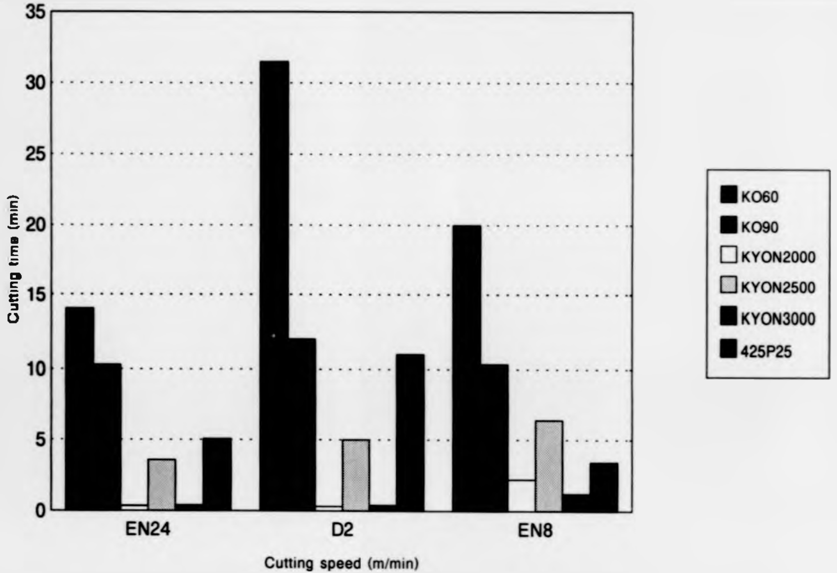

Figure 106 Comparison tool life (min) between the ceramic tools and coated carbide (425P25) at speed of 400 (m/min)

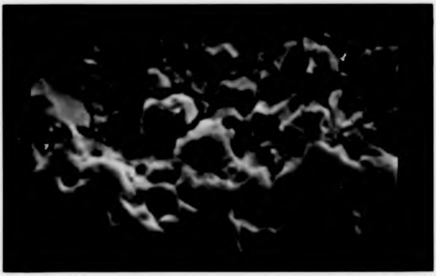

Figure 107 Enlarged view of KO60 tool used for machining EN24 steel at a low speed of 150 m/min showing attrition wear

Figure 108 Severe chipping of the cutting edge when cutting with mixed ceramic KO90 tools at 400 m/min

Figure 109 Showing diffusion wear at a high speed when machining D2 tool steel with KYON 3000 tools

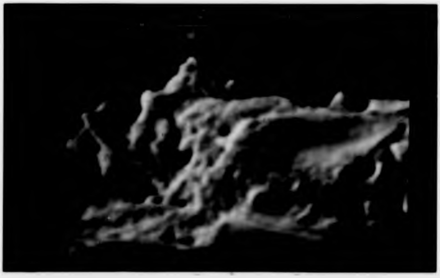

Figure 110 Showing attrition wear when machining steel with ceramic tools

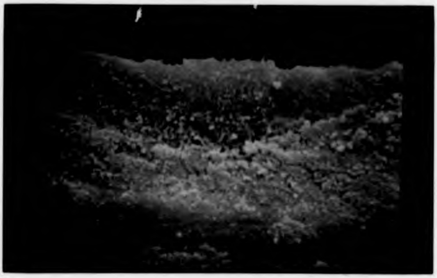

Figure 111 Showing diffusion wear mechanisms when machining steel with ceramic tools

Figure 112 showing plastic deformation when machining steel with ceramic tools

Figure 113 Showing fracture surface and plastic deformation when machining steel with ceramic tools